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VOLUME 6B

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PREFACE

Reports in this volume are numbered consecutively beginning with number 1. Each report is paginated with the report number followed by consecutive page numbers, e.g., 1-1, 1-2, 1-3; 2-1, 2-2, 2-3.

Due to its length, Volume 6 is bound in two parts, 6A and 6B. Volume 6A contains #1-12, and Volume 6B contains reports #13-23. The Table of Contents for Volume 6 is included in both parts.

This document is one of a set of 16 volumes describing the 1995 AFOSR Summer Research Program. The following volumes comprise the set:

<u>VOLUME</u>	<u>TITLE</u>
1	Program Management Report
	<i>Summer Faculty Research Program (SFRP) Reports</i>
2A & 2B	Armstrong Laboratory
3A & 3B	Phillips Laboratory
4	Rome Laboratory
5A, 5B, & 5C	Wright Laboratory
6A & 6B	Arnold Engineering Development Center, Wilford Hall Medical Center and Air Logistics Centers
	<i>Graduate Student Research Program (GSRP) Reports</i>
7A & 7B	Armstrong Laboratory
8	Phillips Laboratory
9	Rome Laboratory
10A & 10B	Wright Laboratory
11	Arnold Engineering Development Center, Wilford Hall Medical Center and Air Logistics Centers
	<i>High School Apprenticeship Program (HSAP) Reports</i>
12A & 12B	Armstrong Laboratory
13	Phillips Laboratory
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SFRP FINAL REPORTS

**FATE AND TRANSPORT OF ORGANIC SOLUBLE PLUMES FROM
SITES 260 AND 280 OF THE HILL AIR FORCE BASE, UTAH**

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Final Report for:
Summer Faculty Research Program
Hill Air Force Base

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Air Force Office of Scientific Research
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and
Hill Air Force Base, Ogden, Utah

September 1995

FATE AND TRANSPORT OF ORGANIC SOLUBLE PLUMES FROM
SITES 260 AND 280 OF THE HILL AIR FORCE BASE, UTAH

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Abstract

Sites 260 and 280 are located in the Hill Air Force Base, Ogden, Utah, and Site 260 is used as a storage location for diesel fuel oils since 1958. Presently Site 260 has six active diesel fuel underground storage tanks (USTs). In August of 1993, free-phase JP-4 jet fuel was detected at these sites at a depth of 109 feet below the ground surface. Since January of 1994, free-product recovery has been performed and a total of 4500 gallons of fuel have been recovered. Present daily recovery from these sites is approximately 50 gallons. Preliminary analysis of organic chemicals in ground water showed the presence of both volatile and semi-volatile compounds in excess of maximum contaminant levels (MCLs). The goal of this study was to investigate the fate and transport of BTX (benzene, toluene, xylene) plumes in ground water under different scenarios and to assess the potential impacts to ground water over time. The analysis was performed using the limited site-data collected by the consultants and using the model BioTrans. The results of the analysis suggested that natural attenuation is possible at the site. However the excessive oxygen demand especially beneath the free-product plume cannot be met with the ambient oxygen in ground water. Enhanced bioremediation through oxygen injection is more promising and should be investigated as a suitable corrective action. Since this analysis was performed under limited site-specific data needed for the model, the results should be used qualitatively. For future corrective action designs, more site-specific data needed for modeling should be collected and used in conjunction with pilot studies to ensure an effective corrective action plan can be implemented.

Introduction

Hill Air Force Base is located in the northern part of Utah and the base has been in operation since 1943. Site 260 of the Hill Air Force Base (HAFB) is located in the southeastern part of the base (Figure 1) and southwest side of Building 260 and the main steam plant. Site 280 is located southeast of Site 260 and west of building 274. The Site 260 was initially built as a storage facility for diesel fuel oil and presently contains six USTs storing diesel fuel. In August of 1993, the area surrounding these sites was investigated for leaking USTs as a routine environmental monitoring check. At that time, approximately 2.5 feet of JP-4 free-phase jet fuel was detected at Site 260. Since that time, a number of monitoring and recovery wells were installed and recovery is continuing from two wells. The total recovery up to present time is approximately 4500 gallons with a daily recovery of 50 gallons. Since the sites were used solely to store diesel fuel and the observed free-product plume consists of JP-4 jet fuel only, it can be concluded that the origin of the free-product plume is from an upstream source rather than from the USTs. Detailed site investigations showed the presence of two free-product plumes (Figure 2). The larger plume in Site 260 is oriented towards the north-south where as the smaller plume in Site 280 is oriented towards east-west. The estimated approximate volume of the free-product plume is 44,000 gallons (Montgomery Watson, 1994).

Preliminary chemical analysis of ground water indicated the presence of both volatile and semi-volatile organic chemicals in excess of respective MCLs. Benzene, toluene, ethylbenzene, and total xylene concentrations ranged from 0.95-16, 0.45-5.2, 0.74-11, 2.2-16 $\mu\text{g/l}$, respectively. TCE was present in ground water since the sites were located within the Operable Unit (OU) 8. In addition, 1,1-Dichloroethane, 1,2-Dichloroethene, and 1,1,1-Trichloroethane were present in relatively low concentrations.

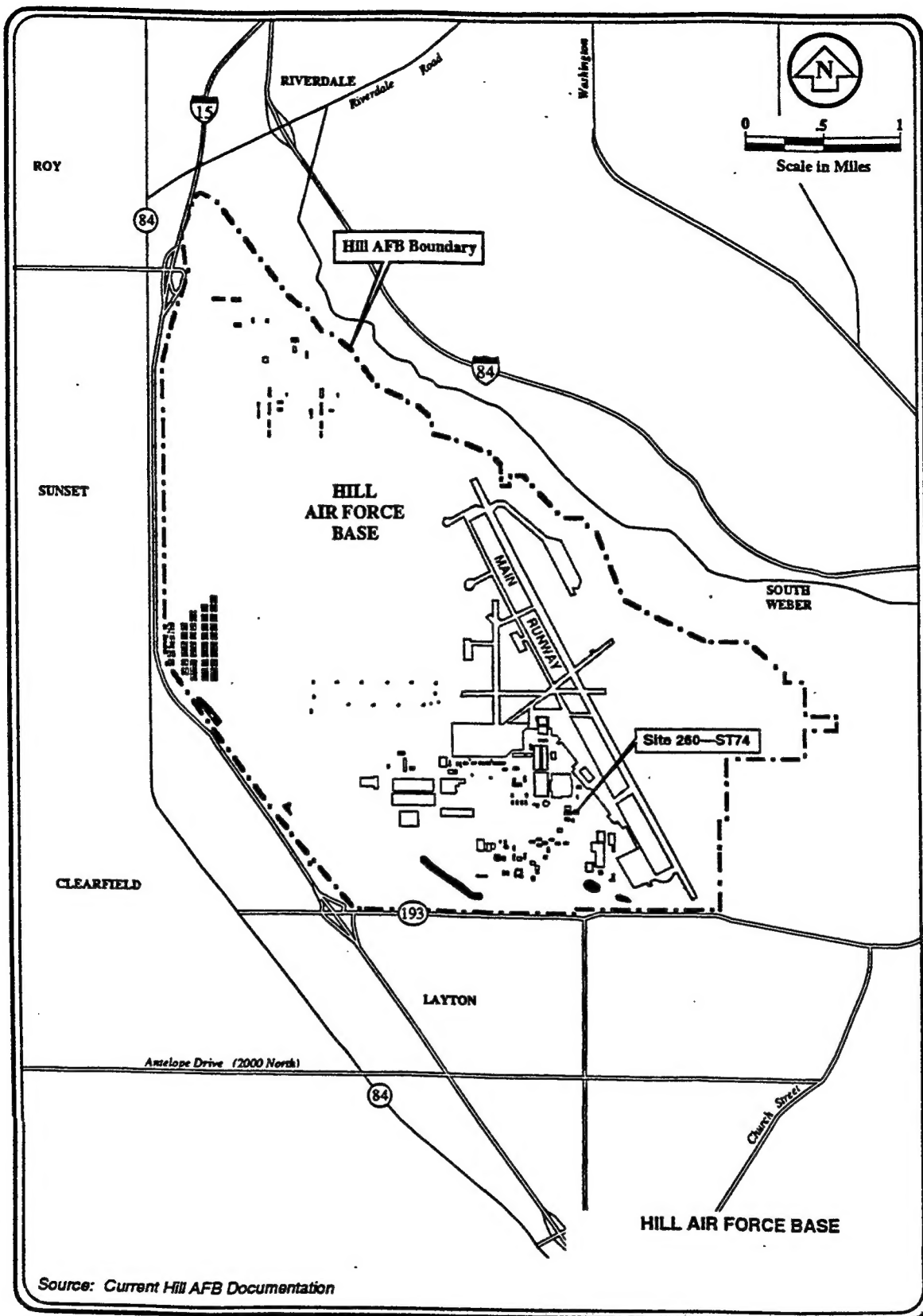


Figure 1. Layout of the Hill Air Force Base.

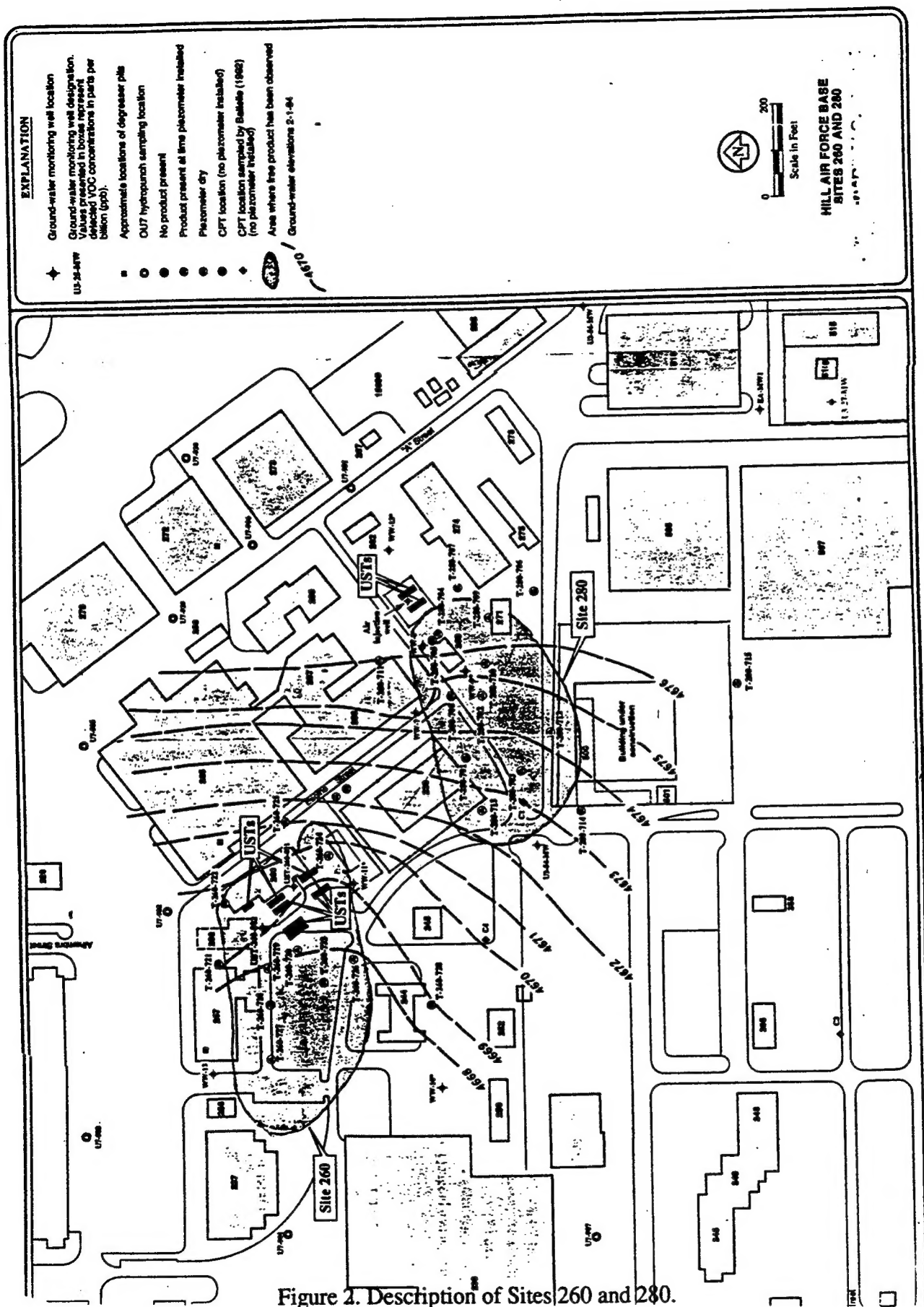


Figure 2. Description of Sites 260 and 280.

Objectives

The main goal of this work was to determine the fate and transport of soluble organic contaminant plumes within the free-product contaminated area. If the results of this work suggests that natural attenuation is possible, at least for the volatile contaminants, then future corrective actions can focus on natural attenuation and continuous monitoring. However if enhanced biodegradation is the only option to reduce the pollution levels in the subsurface, then results of this work will provide preliminary recommendations needed for site investigations and remedial designs.

Site Hydrogeology

Ground water flow at Sites 260 and 280 is towards west-northwest with an estimated hydraulic gradient of approximately 0.009 feet/feet. The depth to the water table is approximately 110 feet below the ground surface. The soil with in the saturated zone varies between well-graded sand to poorly-graded sand with some silt and gravel. The soil profile in this area is highly heterogeneous and only detailed pump tests results can provided accurate information related to conductivity values. There are approximately ten monitoring wells located in this site with two recovery wells for free-product removal. A total of ten bore holes were used in the site investigations and 11 Cone Penetrometer Tests (CPTs) were performed.

Modeling Approach

In order to model the soluble plumes, three organic fractions and a pseudo component representing all other fractions were used in the analysis. The three distinct fractions were benzene, toluene, and total xylene. The mass transfer to the saturated subsurface was from the free-product plume and the fate and transport of the individual constituents were subjected to various transport mechanisms. These transport mechanisms include advection, dispersion with molecular diffusion, solid phase sorption, and decay due to natural attenuation. Natural attenuation consists of aerobic biodegradation due to ambient oxygen in ground water. The model used in the analysis was

BioTrans (ES&T, 1994) which is capable of modeling multicomponent organic chemical transport due to dissolution of an existing free-product plume through rate-limited mass transfer. In addition to the organic chemicals, it is also capable of modeling oxygen transport.

Data collection at these sites is still being conducted by Montgomery Watson of Utah and therefore limited soil and fluid properties were available to perform an accurate analysis. In the absence of detailed site-specific data, some of the properties were obtained from literature that correspond to similar situations. Some of the important information not available from site investigations were saturated hydraulic conductivity from pump test data, solid phase sorption properties, biological decay coefficients, ambient oxygen concentration, mass transfer rates, and dispersion parameters' such as dispersivity. Pump test data is considered to be important since in the presence of substantial subsurface heterogeneity, pump tests can provide valuable information on soil hydraulic conductivity. Also bio-activity is heavily dependent on the ambient oxygen concentration. The actual mass of contaminant in ground water for corrective actions is dependent on the mass transfer behaviors. Some of these properties can be obtained from rigorous model calibration. However this step could not be performed since time series behavior of soluble plumes were not available from site observations. Due to these major limitations of data, results of this modeling study should be viewed as preliminary and qualitative. Final corrective actions should be designed using additional site-specific data collected based on this report recommendations.

Simulation Scenarios

The analysis is focused on determining the potentials for natural attenuation and the fate and transport pattern of chemicals during the simulation period. The only mechanism considered here for natural attenuation is aerobic degradation due to oxygen. The saturated hydraulic conductivity used in the simulation is 11.5 feet/day and this value corresponds to that of loam soil since the soil type varies between well-graded sand to poorly-graded sand with some fines. Therefore using the USDA classification (ES&T, 1994), loam soil was considered as the representative soil for an

equivalent homogeneous medium. The gradient of ground water flow is 0.009 feet per feet and in the direction of west-northwest. The mass fractions were computed using the data of Montgomery Watson, 1994a, and the values for benzene, toluene, xylene, and pseudo fraction were 0.12, 0.18, 0.3, and 0.4, respectively. The molecular weights in the same order were 78.1, 92.1, 106.2, and 205.7 g/mole. The bulk density, total porosity, longitudinal dispersivity and transverse dispersivity were 1.6 g/cc, 0.3, 25 feet, and 3 feet, respectively. The solubility of benzene, toluene, and xylene were 1780, 515, and 175 mg/l, respectively. The base case oil-water mass transfer coefficient used was 0.03. Ambient oxygen concentration used was 6 mg/l. The remaining fluid properties were best estimated from the guidelines provided in the BioTrans manual to represent conditions at these sites.

The different scenarios considered in the analysis can be summarized as follows:

- I. Base case simulation of natural attenuation through aerobic degradation with a oil-water mass transfer coefficient of 0.03.
 - II. Same as simulation I except the mass transfer rate was reduced to 0.003.
 - III. Same as simulation I except the mass-transfer rate was reduced to 0.001.
 - IV. Same as the base case except oxygen is injected from two locations at a rate of 50 g/day. One location is in the upper plume where as the second location is in the lower plume.
- All simulations were conducted for a period of 20 years which corresponds to twenty years since the free-product plumes were produced.

Results and Discussion

Figures 3 through 6 show the distribution of benzene for different scenarios. As expected, the base case produced the largest plume followed by Scenario II and III. The reason for the largest plume with the base case is the highest mass transfer coefficient of 0.03. Scenarios II and III used gradually decreasing mass transfer rates of 0.003 and 0.001. These results are further

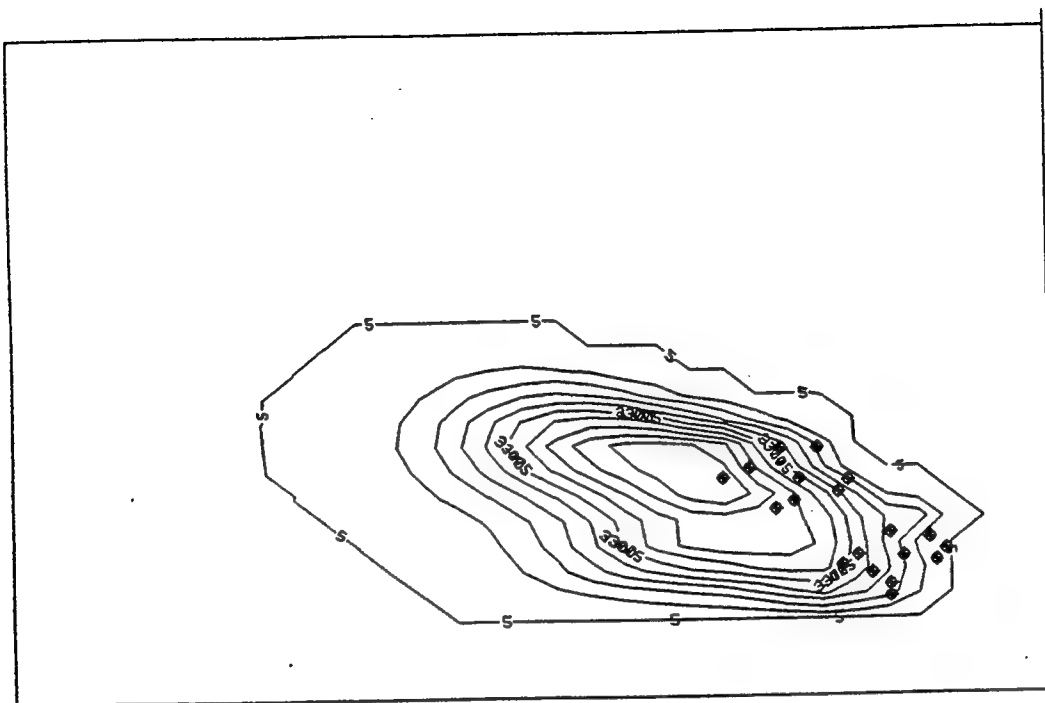


Figure 3. Ground water concentration distribution of benzene ($\mu\text{g/l}$) at 20 years for Scenario I.

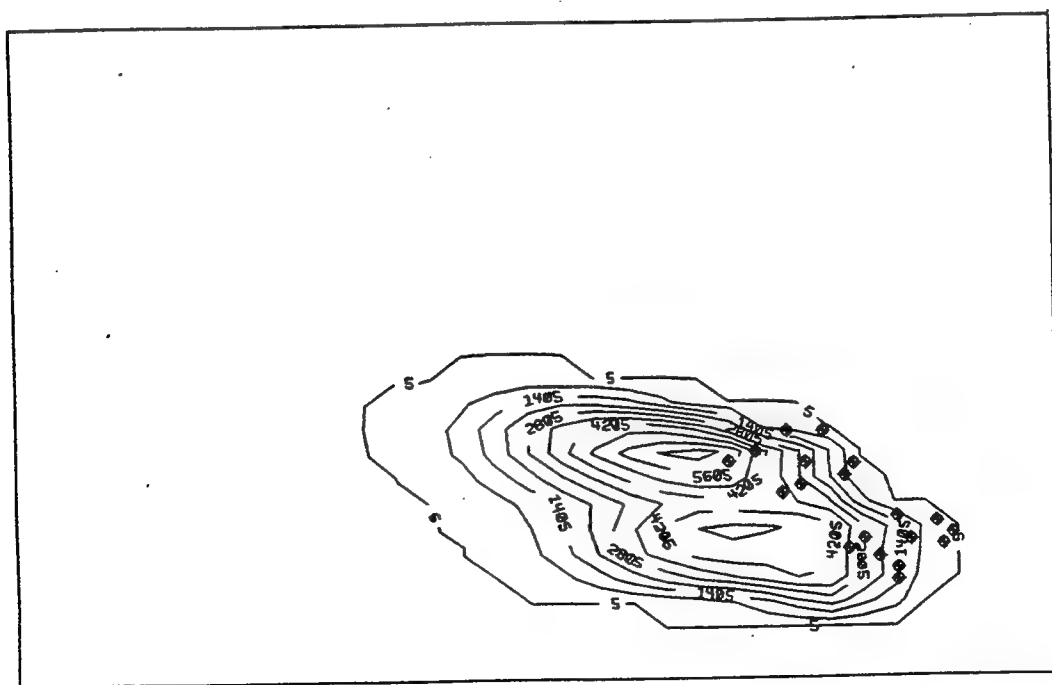


Figure 4. Ground water concentration distribution of benzene ($\mu\text{g/l}$) at 20 years for Scenario II.

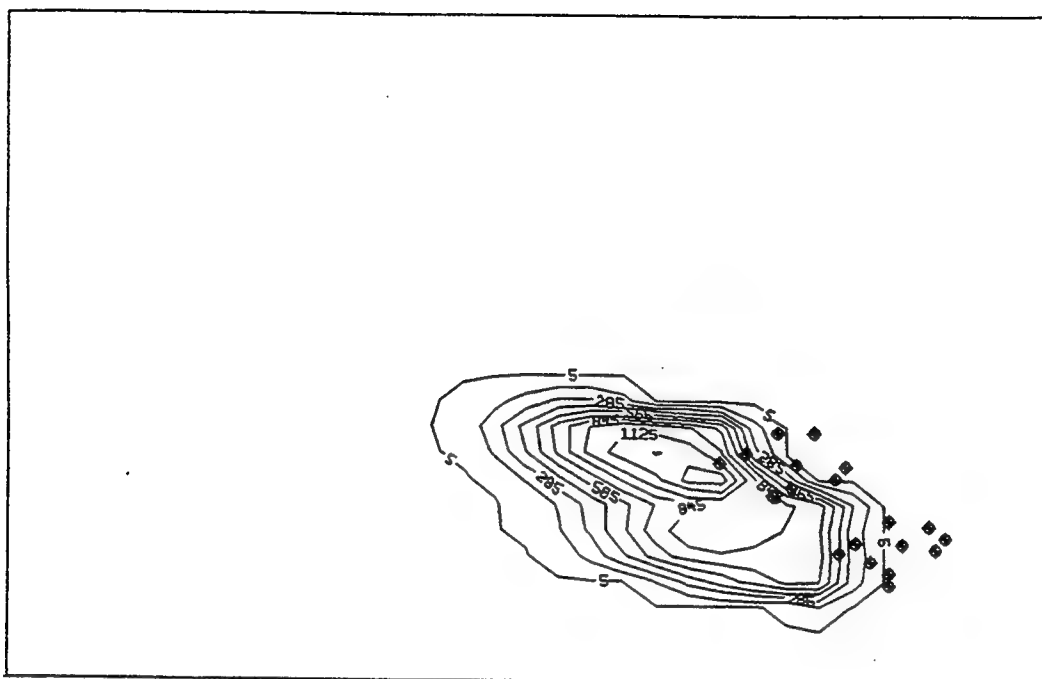


Figure 5. Ground water concentration distribution of benzene ($\mu\text{g/l}$) at 20 years for Scenario III.

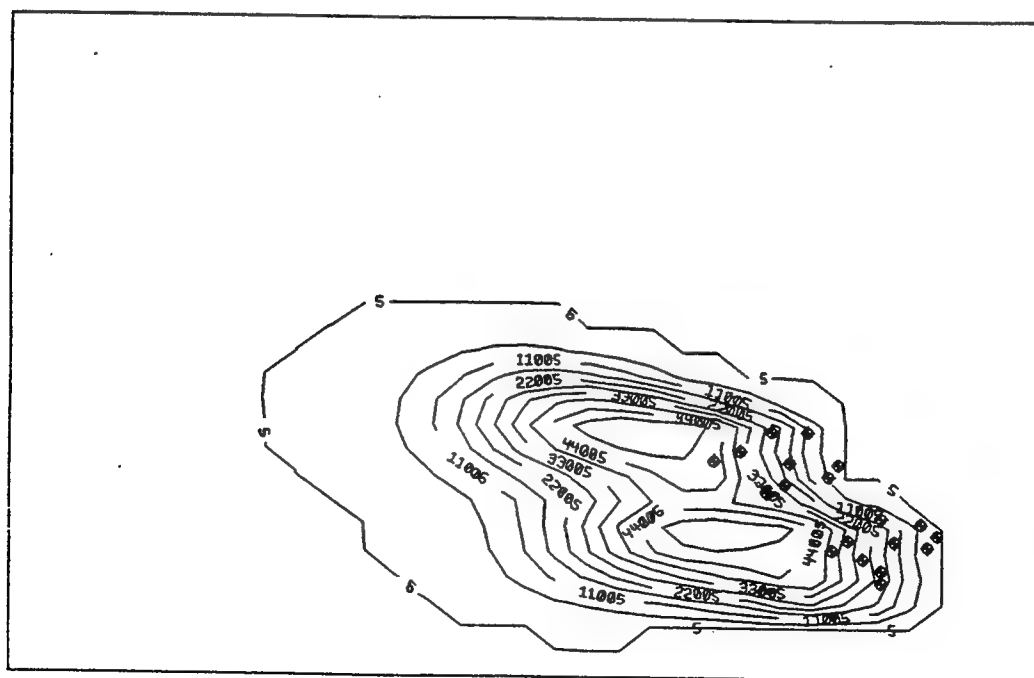


Figure 6. Ground water concentration distribution of benzene ($\mu\text{g/l}$) at 20 years for Scenario IV.

demonstrated in Tables 1 through 3 where the longitudinal spreading lengths varied from 2500 feet to 1340 feet, and similarly the transverse spread varied from 1500 to 984 feet for Scenarios I through III. The maximum concentrations were also highest with the base case due to the largest dissolution rate of the free-product plume. The benzene maximum concentration was high as 66 mg/l with the base case and reduced to 1.4 mg/l with the lowest mass transfer rate of 0.001. Although not shown here, oxygen concentrations beneath the free-product area became almost negligible due to rapid biodegradation of the contaminants.

The scenario IV is similar to the base case except that oxygen was injected from two locations at a rate of 50 g/day. It is seen from Figures 3 and 6 that actual spread areas of the benzene plumes were similar but the maximum concentration near the free-product plumes reduced due to increased aerobic degradation. This observation is demonstrated in Figures 7 and 8 where the contaminant concentrations are plotted at a monitoring well located in the upper free-product plume. It is seen that the maximum benzene concentration reduced with Scenario IV due to increased oxygen supply to the plume area. For example, maximum benzene concentration in this well reduced from approximately 50 mg/l to less than 35 mg/l from natural attenuation to enhanced bioremediation. Tables 1 and 4 show that the maximum benzene concentration for the entire area reduced from 66 mg/l to 55 mg/l due to increased oxygen supply.

Results obtained with toluene are also shown in Figures 9 through 12. Once again, the results are qualitatively similar to that of benzene except that the actual travel distances and the maximum concentrations are smaller. These observations are not surprising since toluene has a small aqueous phase solubility than benzene, 1780 versus 515 mg/l, and a higher molecular weight.

The contour plots of xylene in ground water are not shown here except the summary in Tables 1 through 4 since the results are qualitatively similar to benzene and toluene.

Table 1. Descriptions of the Contaminant Plumes after 20 Years for Scenario I.

Contaminant	Maximum Longitudinal Spread (feet)	Maximum Transverse Spread (feet)	Maximum Concentration (µg/l)
Benzene	2500	1500	65849
Toluene	2000	1500	21150
Xylene	1125	1375	5868

Table 2. Descriptions of the Contaminant Plumes after 20 Years for Scenario II.

Contaminant	Maximum Longitudinal Spread (feet)	Maximum Transverse Spread (feet)	Maximum Concentration (µg/l)
Benzene	2000	1313	6585
Toluene	1500	1250	2056
Xylene	813	1188	551

Table 3. Descriptions of the Contaminant Plumes after 20 Years for Scenario III.

Contaminant	Maximum Longitudinal Spread (feet)	Maximum Transverse Spread (feet)	Maximum Concentration (µg/l)
Benzene	1340	1188	1353
Toluene	1313	984	423
Xylene	625	875	139

Table 4. Descriptions of the Contaminant Plumes after 20 Years for Scenario IV.

Contaminant	Maximum Longitudinal Spread (feet)	Maximum Transverse Spread (feet)	Maximum Concentration (µg/l)
Benzene	2428	1665	54962
Toluene	1943	1665	19090
Xylene	1110	1526	5868

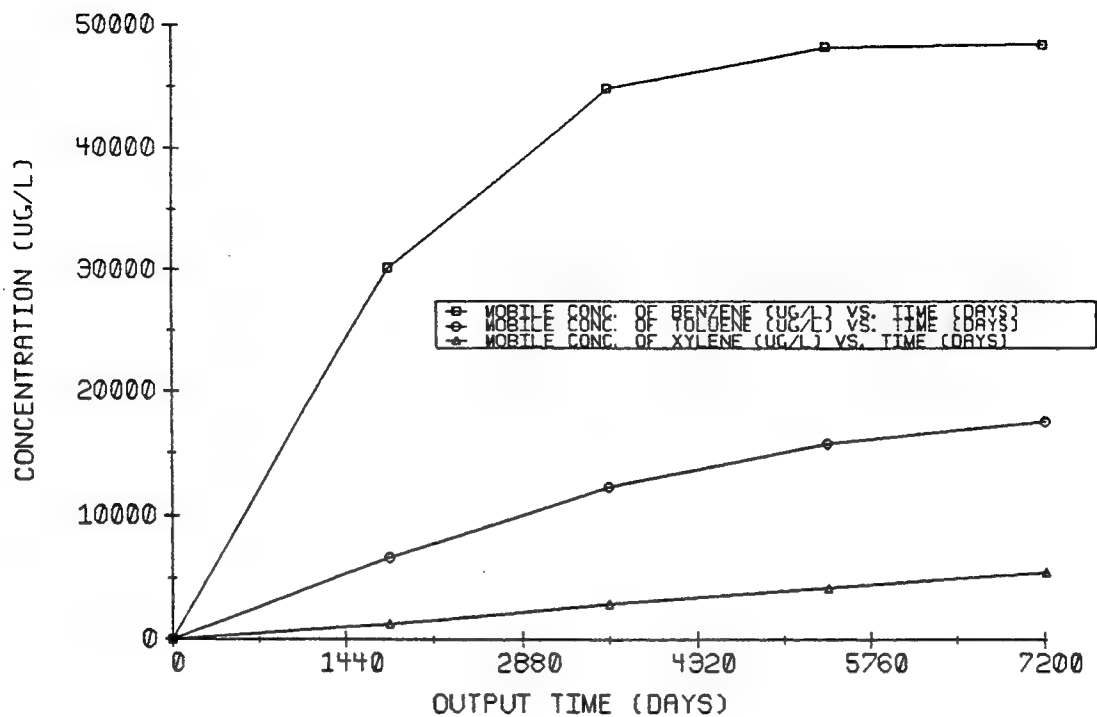


Figure 7. Ground water concentration distribution of benzene ($\mu\text{g/l}$) with time at a monitoring well location within the upper free-product plume area; Scenario I.

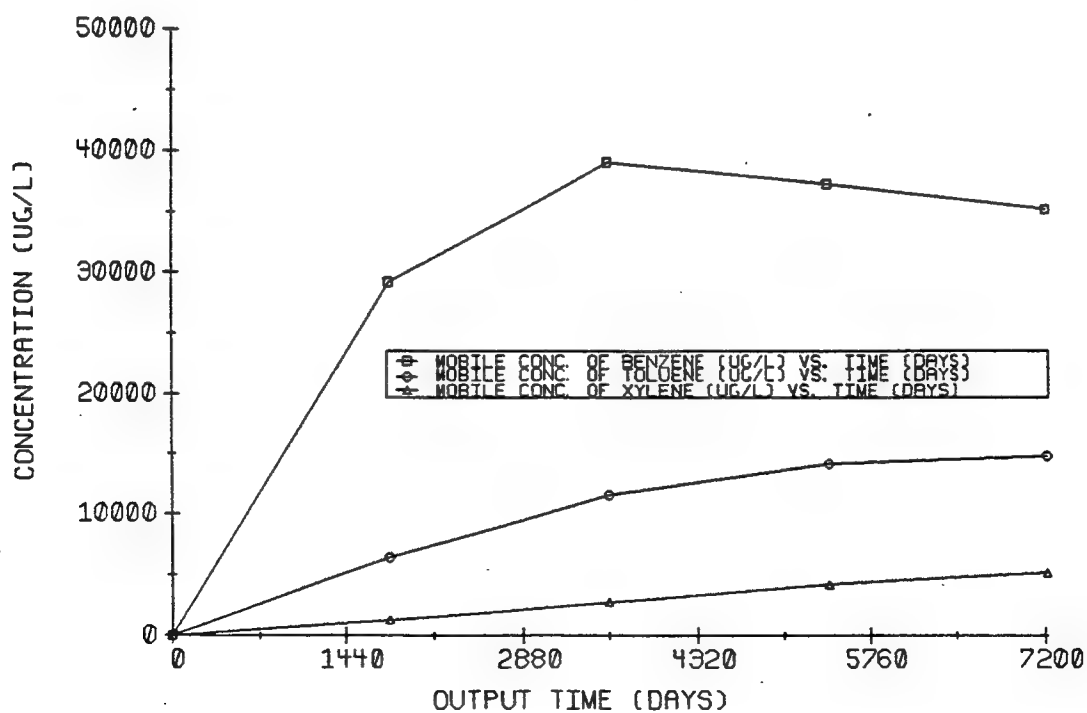
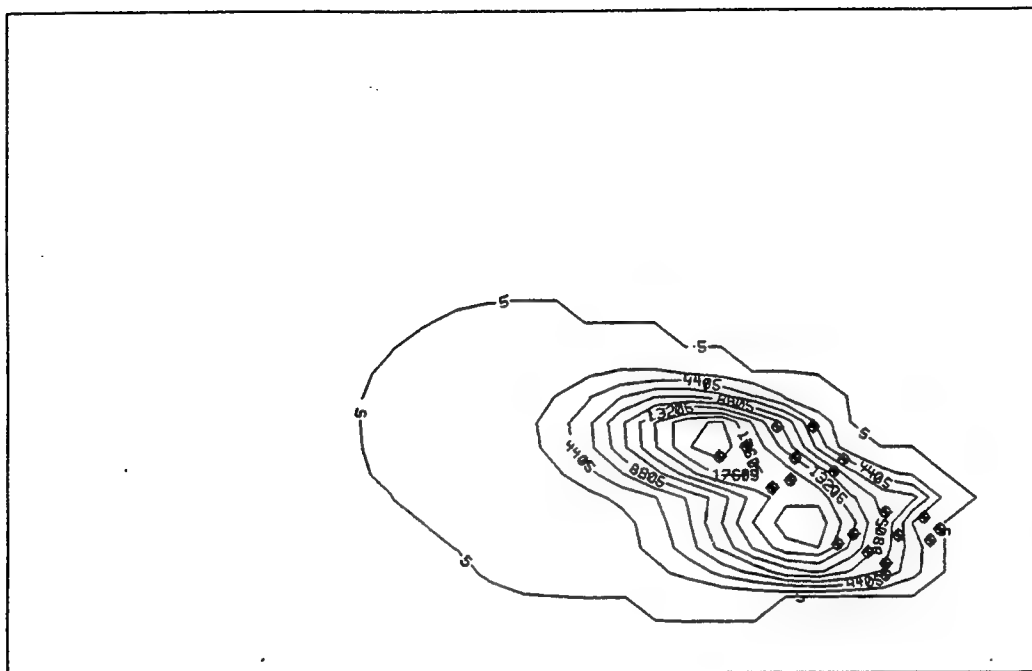


Figure 8. Ground water concentration distribution of benzene ($\mu\text{g/l}$) with time at a monitoring well location within the upper free-product plume area; Scenario IV.



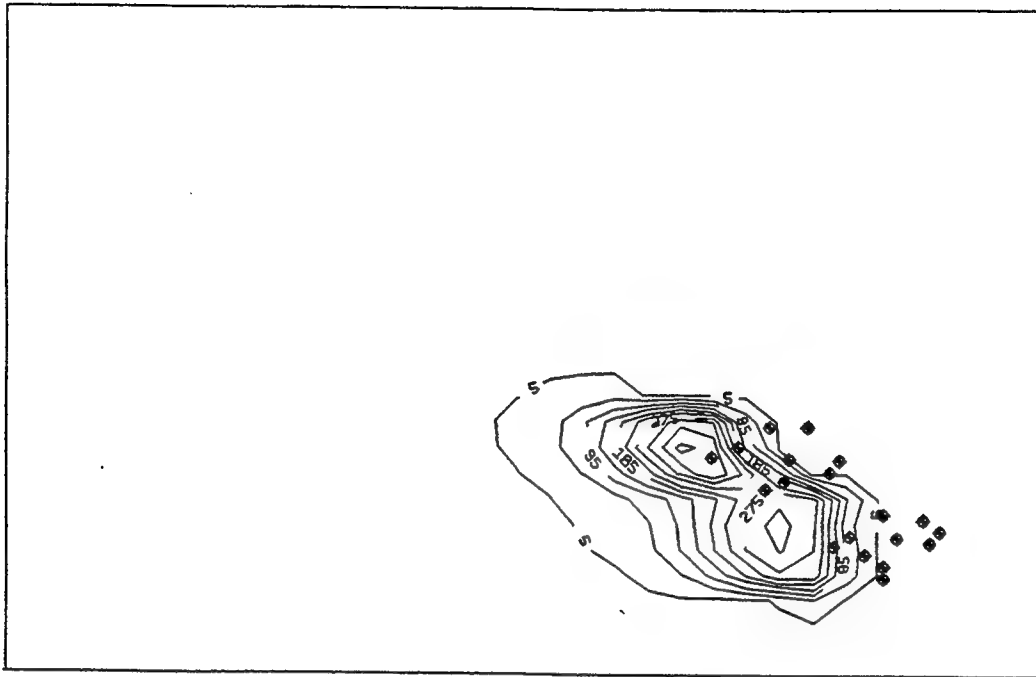


Figure 11. Ground water concentration distribution of toluene ($\mu\text{g/l}$) at 20 years for Scenario III.

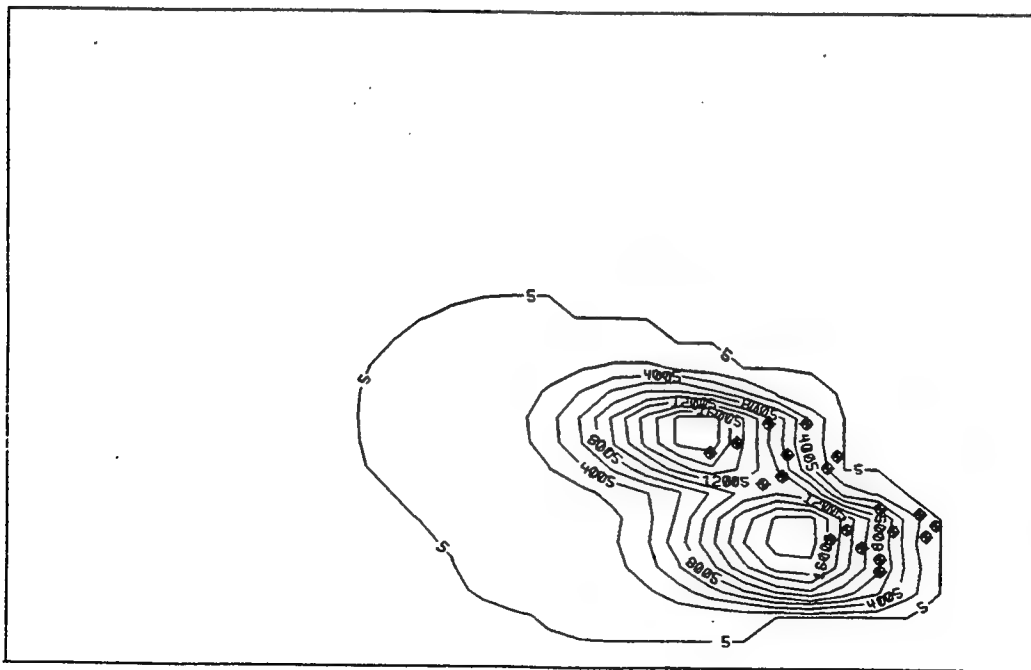


Figure 12. Ground water concentration distribution of toluene ($\mu\text{g/l}$) at 20 years for Scenario IV.

Conclusions and Recommendations

Results of this preliminary analysis of fate and transport of soluble organic plumes at Sites 260 and 280 showed that natural attenuation through aerobic degradation is a potential mechanism to reduce the concentration levels in ground water. However the ambient oxygen concentration alone is not capable to meet the demand due to rapid depletion of oxygen within the plume. Enhanced biodegradation through oxygen injection can enhance plume reduction and should be investigated more carefully as a potential corrective action. However, final decision on the actual design should be made after obtaining more site-specific information related to fate and transport parameters and bio-activity indicators. Since the analysis performed in this study was based on limited site observed data and a large number of assumed soil and fluid properties, these results only provide qualitative nature of the problem.

Future monitoring activity in this study should focus on obtaining soil hydraulic conductivity data from more conclusive pump tests, adsorption properties of the soil, bioactivity data such as biodegradation rates, and mass transfer rates. Although some of these data can be measured either in-situ or through undisturbed column studies, it is also possible to use model calibration techniques to estimate some of the important parameters. However for this purpose, more accurate time series data of ground water concentration may be required. Although heavy metals were not present in this site, at least in traceable limits, further investigations should be performed to ensure toxic effects are not present at the site to prevent efficient biodegradation. As a final step, pilot studies related to enhanced bioremediation should be performed before final implementation of the corrective action plan to ensure adequate electron acceptors and nutrients are present in the subsurface. Although pump and treat can be an expensive and a time consuming technology, it may be worth to explore the possibility of using a combined technique of pump and treat together with enhanced bioremediation.

The analysis performed in this study did not consider the impact of TCE in ground water due to the presence of OU-8 ground water plumes. Further field investigation should be performed to understand the effects of additional ground water contaminant input from OU-8 to Sites 260 and 280.

References

- Environmental Systems & Technologies, Inc., User Guide to BioTrans, Version 5.0, Blacksburg, Virginia, 1994.
- Montgomery Watson, Subsurface Investigation Report, Corrective Action Plan, and Free-Product Removal Report for UST Site 260 (ST74), Submitted to Hill Air Force Base, Utah, 1994.

**AN ARTIFICIAL NEURAL NETWORK CLASSIFIER
FOR MULTI-MODAL DISTRIBUTED CLASSES**

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Final Report

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Abstract

The current classification system of the Neural Radiant Energy Detection System requires enhancement to its pattern discrimination algorithm to deal with classes which are multi-modally distributed and formed from sets of disjoint pattern clusters. In order to address this problem within the context of real-time environments, a novel neural network classifier algorithm, the Probabilistic Potential Function Neural Network, which has a number of desirable properties is designed. The proposed neural network has the theoretical promise to offer fast training speed, to configure a minimal network topology during training for a given problem, to learn incrementally (starting with a small number of training samples), to form classification boundaries which optimally separate classes and to manage classes which are likely to be formed from a set of disjoint subclasses in the pattern space where each class is possibly multi-modally distributed.

1. INTRODUCTION

A thermal (infra-red) imaging system, Neural Radiant Energy Detection System (NREDS), has been successfully applied to diagnose faults in electronic circuit cards in OO-ALC/TISAA. The system currently employs a Bayesian classification scheme as the decision making algorithm to identify faulty components. Throughout the course of the operational testing of the thermal imaging system, it has been observed that patterns employed by the classification algorithm are random variables and pattern classes are likely to possess multi-modal distributions and to be formed from many pattern clusters located across the pattern space. Performance of the current classification algorithm degrades significantly for such classes.

Neural networks (NN) which represent a subset of algorithms in statistical pattern recognition theory are paradigms designed with maximum computational efficiency [Werbos, 1991]. NNs offer a number important features which are likely to aid in resolving the challenges NREDS classification task faces; NNs can form arbitrarily complex decision boundaries, offer parallel computing capability, can be implemented in hardware for real-time operation, and can learn from examples [Werbos, 1994]. In order to benefit NREDS from all potential promises of NNs, a "neural solution" to the classification problem will be developed. The proposed NN classifier will have the following features:

1. train on-line (fast learning speed) and classify in real-time (due to parallel computation),
2. form classification boundaries which optimally separate the classes which are likely to be formed from a set of disconnected subclasses in the pattern space; the joint probability density function (PDF) of a particular class is likely to have many modes,
3. does not require an initial guess for the network topology, rather topologically adapt to particular instance of the classification problem at hand in a dynamic way as the training progresses,

4. discover clustering properties of training data and adapt to a minimal network topology in terms of needed computational resources,
5. implement incremental learning procedure and hence, does not disturb the previous state of the network but simply add to it (learning should be accomplished simply by adding new computational resources to the existing network topology to learn the new training pattern), and
6. form optimal decision boundaries which approximate those of theoretical Bayesian classifier.

2. BACKGROUND

2.1. Description of NREDS Classification Subsystem

The NREDS classification algorithm performs a two-level procedure to isolate the faulty components on a given circuit card. Initially, a card-level decision is made to classify a given board into one of two classes; the class of operational cards and the class of non-operational cards. The classification algorithm used is the Bayes classifier [Allred et al., 1992]. The input to the classifier is an $n \times 1$ vector components of which are the temperature rise rates associated with each of n components on the circuit card. The output of the Bayes classifier is the probability of the card under test belonging to the class of operational cards. Additionally, a confidence measure is computed.

Once a card is classified into the non-operational class, then each component is analyzed to assess its condition. Features for components (there is only one feature for each component which is the peak temperature change rate) on an operational card are provided to the algorithm. The peak heat change rate of each component is assumed to be a normally distributed random variable. The underlying univariate Gaussian PDF for the peak heat rate change of a component is defined by

$$p(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp \left[-\frac{1}{2} \left(\frac{x - \mu}{\sigma} \right)^2 \right] \quad (1)$$

where μ and σ are the mean (measured peak heat change rate) and the standard deviation (assumed a priori based on empirical observations) of the PDF for the random variable x (peak heat change rate) [Allred et al., 1992]. For each component on a non-operational card, its peak temperature change rate is compared against the range of acceptable values computed using the mean and standard deviation associated with the same component on an operational card. Any component outside the relevant range is declared to be a "candidate" for faulty operation.

Given that there are n components on a card, $\bar{x} = [x_1, x_2, \dots, x_n]^T$, the multivariate conditional PDF of \bar{x} (pattern vector representing a card) for a class, ω_i , can be formed as

$$p(\bar{x} / \omega_i) = \frac{1}{(2\pi)^{n/2} |C_i|^{1/2}} \exp \left[-\frac{1}{2} (\bar{x} - \bar{\mu}_i)^T C_i^{-1} (\bar{x} - \bar{\mu}_i) \right], \quad i = 1, 2, \dots, M \quad (2)$$

where $\bar{\mu}_i$ is the mean vector and C_i is the covariance matrix of the class, ω_i , and M is the number of classes. Note that the overall class PDF is assumed to be a normally distributed function for which the class mean vector, $\bar{\mu}_i$, and the class covariance matrix, C_i , need to be estimated using the set of available data samples. However, it must be noted that an incremental Bayesian learning of the mean vector and the covariance matrix is feasible (see the reference by Tou & Gonzalez [1981] for further details) for the cases where initial data is not readily available for estimation computations.

Equation 2 requires on the order of n^2 parameters which consists of the elements of the mean vector and the covariance matrix to be available. In essence, elements of the mean vector and the covariance matrix for the class needs to be estimated using observed samples. In almost all application domains of the NREDS, a large enough training data set on which meaningful statistical quantities can be computed is not available (each functionally different circuit card is considered as a new problem). As a result, an approximation, which requires much less number of parameters to be estimated, given by Equation 3 to the multivariate class PDF, Equation 2, is employed.

$$p(\bar{x} / \omega_i) = \prod_{j=1}^n \frac{1}{\sqrt{2\pi}\sigma_{ji}} \exp\left[-\frac{1}{2\sigma_j^2}(x_j - \mu_{ji})^2\right] \quad (3)$$

Note that Equation 3 can also algebraically be obtained from Equation 2 employing the independence assumption for univariate distributions. Assuming that the univariate distributions for individual training sample patterns are independent will result in the off-diagonal terms of the covariance matrix to be zero and hence, Equation 2 will lead to Equation 3.

Components are likely to fail in multiple ways with heat rate signatures depicting large variations due to those many modes of failures. Additionally, a failure in one component is likely to affect modes of operation for other components in the same circuit resulting in different heat rate signatures for those components. As an example, a diode will have different failure characteristic in terms of its heat rate signature depending on if it fails in one of following ways. Some of the modes a diode can fail consists of hard failures including open-circuit or short-circuit conditions or soft failures including drastic changes in current-voltage characteristics or in operational point of the diode will be reflected with large variations in the heat change rate signatures. The effect of multi-mode failures of a particular component will translate into changing the location of the pattern vector for the card noticeably in the pattern space therefore, leading to multi-modality and adding a disjoint cluster to the overall failure class.

The main underlying assumption in the current data model using Equation 2 or 3 is that a uni-modal normal distribution can accurately model the true class density. The class PDF given by either Equation 2 or Equation 3 will fail to adequately approximate the actual class PDF if pattern sets are clustered in separated and disconnected regions of the patterns space. Specifically, there are two reasons why Equation 2 or 3 will not be a good estimator for the true class density. The estimate of the class PDF fails to model the multi-modality of data and tends to cover regions, which do not belong to the actual class density, if that region falls in-between those two possibly disconnected regions belonging to the true class density in the pattern space. In summary, the model PDF defined by Equation 2 to approximate the true class density is not an appropriate one, simply because

the estimate will deviate from the true density significantly for the NREDS data. Therefore, a better model, if it exists, should be used as an estimate of the true class PDF.

3. PROPOSED IMPROVEMENTS TO NREDS CLASSIFIER

The approximation to the true class PDF given by Equation 3 results in large deviations from the actual density for distributions which are multi-modal and represent classes formed from disjoint clusters spread throughout the pattern space. Therefore, initial efforts concentrated on identification of a better estimator for the class PDFs. For the problem at hand, a better approximation to the true class PDF (in the sense that it protects the clustering properties of the data) is given by the Parzen estimator. Parzen [1962] showed that

$$f_{\omega_i}(\bar{x}) = \frac{1}{\sqrt{(2\pi)^n} \sigma^n K} \sum_{j=1}^{K_i} \exp \left[-\frac{(\bar{x} - \bar{x}_j)^T (\bar{x} - \bar{x}_j)}{2\sigma^2} \right], \quad (4)$$

where n is the dimensionality of a pattern, K_i is the number of patterns in class ω_i and σ is a smoothing parameter, will approach the underlying class density if the class density is smooth and continuous. Note that this estimate of the defines a class PDF which preserves the multi-modality and the clustering properties of the training data, which is very desirable for the classification algorithm.

The neural network which most suitably utilizes Parzen's estimate of the true class PDF is the Probabilistic Neural Network (PNN) [Specht, 1989]. The PNN paradigm has a number of significant deficiencies, among which the need to create one hidden layer node for each training pattern is an important one, which are likely to render this algorithm not suitable for NREDS implementation. To be able to reduce the number of hidden layer nodes, it might be necessary to pre-process the training pattern set. In a typical pre-processing step, a classical clustering algorithm like the k -means may be applied to the training pattern set before it is used to train the network. A second method to prevent the

node count in the hidden layer of the network from growing unacceptably is to revise the training algorithm and add a new pattern node if the PNN is not able to classify the newly presented training sample correctly with a desired minimum confidence level.

4. PROPOSED NEURAL NETWORK ALGORITHMS

4.1. Survey of Neural Network Pattern Classifiers

The set of significant neural network paradigms which implement pattern classification tasks include multi-layer perceptron (MLP) network, radial basis function (RBF) network, learning vector quantizer (LVQ) network and probabilistic neural network (PNN). All these networks possess important shortcomings. In the following paragraphs, each network paradigm is briefly criticized for its strengths and weaknesses and reasons for not considering the particular paradigm for the NREDS classification task are explained.

The MLP with Backpropagation learning rule is the most widely known neural network algorithm for pattern classification. The lack of efficient techniques to determine the topology of the network for a given problem and the slow learning speed make this paradigm unsuitable for real-time implementations [Werbos, 1994]. It is well documented in the literature that the number of hidden layer nodes play a very important role in the ability of the network to partition the pattern space and there does not exist analytical procedures to specify the number of hidden layer nodes for a particular problem except in a number of limited cases [Leshno et al. 1993].

RBF neural networks can be trained up to three orders of magnitude faster than MLP's for the same type of problems [Poggio, 1994; Lipmann, 1994]. Initialization of the network requires clustering properties of the data to be analyzed and understood well, which is typically performed using an unsupervised learning algorithm like the k -means and is essential to determine the number of hidden layer nodes and their parameter settings. The training process requires matrix inversion operation to be performed to compute the weights from the hidden layer to the output layer. It is possible that a lack of understanding of the clustering properties of the data may cause an insufficient network

topology to be specified, which in turn will cause the network performance to suffer significantly.

LVQ networks can be trained very efficiently compared to and demonstrate a classification performance no worse than other powerful paradigms like MLP and RBF networks [Kohonen, 1991]. This paradigm suffers significant performance degradation if the codebook vectors cannot be initialized optimally, for which no well-defined procedure exists [Pal et al., 1993]. The effect of initialization on the network performance gets worse if the class distributions are disjoint and maybe even intermingled.

The PNN possesses a number of important useful characteristics like the ease of setting it up, simplicity of training and ability to perform in real-time for most applications once the network is trained. The PNN paradigm requires a pattern layer node to be created and tuned to (weight vector of the newly created node is set to the training pattern) for each training pattern, which might result in very large node counts for the pattern layer. For applications where learning needs to be performed while the previously learned information is retained, it is highly possible that the pattern layer will have an excessive number of nodes.

Unique yet practical requirements of NREDS classification task disqualified all four main neural network paradigms, which are MLP, RBF, LVQ and PNN, as candidates for a classifier algorithm. Resultant search for a suitable neural network classifier led to the design of two new neural network algorithms; one network for each of two cases: deterministic and stochastic decision making.

4.2. Potential Function Neural Network (PFNN)

Consider a pattern classification problem with two classes which are separable and the pattern clusters forming a particular class are not necessarily connected in the n -dimensional pattern space. A trainable and deterministic pattern classifier which can perform successfully for problems under those conditions is the potential function method [Tou & Gonzalez, 1981]. The PFNN is a neural network implementation of the well-known potential function pattern classification algorithm. The basis of the potential function or PFNN algorithm requires each sample point in class ω_1 to be assigned a

maximum positive value and that value to quickly decrease as one travels away from that point in any direction. Similarly, the technique also requires each sample point in class ω_2 to be assigned a maximum negative value and that value to increase rapidly towards zero as one goes further away from that sample point in any direction. These statements are formalized in the following section.

4.2.1 Mathematical Model*

The PFNN will construct decision functions of the form

$$d(\bar{x}) = \sum_{i=1}^{\infty} c_i \varphi_i(\bar{x}) \quad (5)$$

where $\varphi_i(\bar{x})$, $i = 1, 2, \dots$, are orthonormal functions, and c_i , $i = 1, 2, \dots$, are unknown coefficients which can be determined from training pattern vectors. Computation of the decision function will be based on potential functions which are defined for any sample pattern point \bar{x}_k as

$$K(\bar{x}, \bar{x}_k) = \sum_{i=1}^{\infty} \lambda_i^2 \varphi_i(\bar{x}) \varphi_i(\bar{x}_k) \quad (6)$$

where λ_i , $i = 1, 2, \dots$, are real numbers (not zero) chosen to make the potential function bounded for $\bar{x}_k \in \omega_1 \cup \omega_2$. An iterative formula which relates the decision function to the potential function is derived in [Tou & Gonzalez, 1981] and given by

$$d_{k+1}(\bar{x}) = d_k(\bar{x}) + r_{k+1} K(\bar{x}, \bar{x}_{k+1}) \quad (7)$$

where the coefficient r_{k+1} is defined as

* This discussion is based on section 5.6, Pattern Recognition Principles by Tou, J. T. and Gonzalez, R. C., Addison-Wesley Publishing Company.

$$r_{k+1} = \frac{1}{2} a_{k+1} \{1 - a_{k+1} \operatorname{sgn}[d_k(\bar{x}_{k+1})]\} \quad (8)$$

$$\text{with } a_{k+1} = \begin{cases} +1 & \text{for } \bar{x}_{k+1} \in \omega_1 \\ -1 & \text{for } \bar{x}_{k+1} \in \omega_2 \end{cases}.$$

A typical potential function commonly used, although not in the form given by Equation 6, is given by (see reference [Tou & Gonzalez] for further details),

$$K(\bar{x}, \bar{x}_k) = e^{-\alpha \|\bar{x} - \bar{x}_k\|^2}, \quad \alpha > 0 \quad (9)$$

which is a symmetric function of two variables and mathematically expandable in an infinite series.

4.2.2. PFNN Architecture

The PFNN has three layers: an input layer which essentially distributes the feature vector to next layer nodes, a hidden layer and an output layer. Number of nodes in the input layer is equal to the dimensionality of the feature vector. Node count for the hidden layer is determined during the training process and closely related to the clustering properties of the training data. Output layer will have only one node for a two-class categorization problem.

Nodes in the input layer implement the identity mapping function and provide the feature vector to hidden layer nodes without weighting. Each hidden layer node represents a cluster center in the feature space and, as a first stage of processing, will compute the squared Euclidean distance between the incoming feature vector and the cluster center it represents. Next step of processing inside the hidden layer node is to pass the distance measure through an exponential function. The overall input-output relationship for a hidden layer node is given by

$$o_i^{hidden} = e^{-\alpha \|\bar{o}^{input} - \bar{x}\|^2},$$

where \bar{o}^{input} is the input (feature) vector, α is the spread of the function, and \bar{x} is the cluster center learned during training. Output of the hidden layer node is provided, through a fixed weight connection (value of which is determined during the training time as either 1 or -1), to the output layer node. First stage processing in the output layer node is to algebraically sum the incoming signals and then pass that sum through a binary threshold function. The input-output relationship for an output layer node is defined by

$$o^{output} = \text{sgn} \left[\sum_{i=1}^H w_i o_i^{hidden} \right],$$

where H is the number of nodes in the hidden layer and w_i is the fixed weight (equal to either +1 or -1) between the output layer node and hidden layer node i . Graphical description of the topology of the neural network is given in Figure 1.

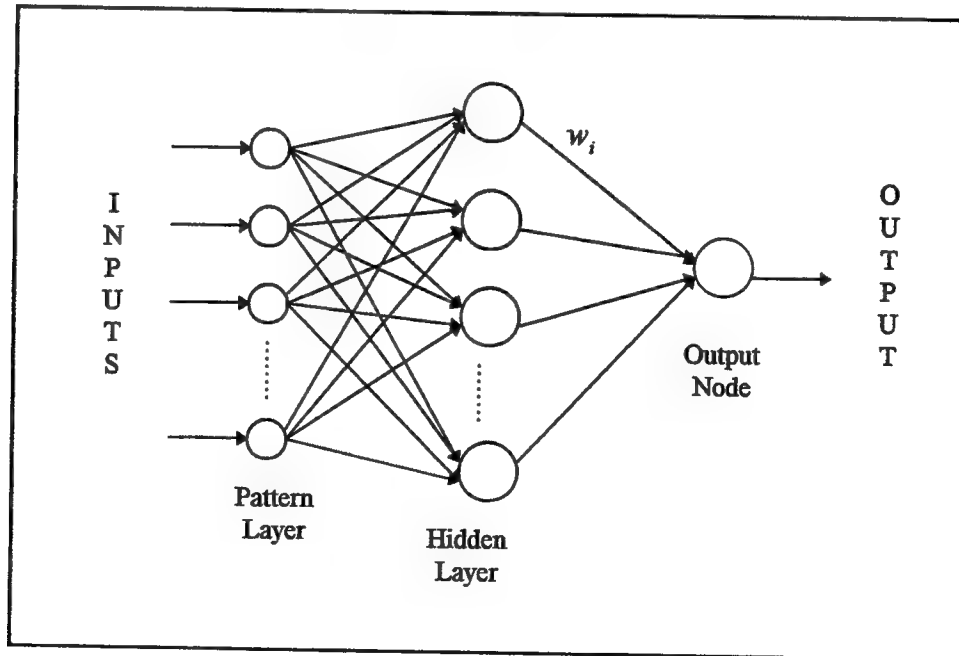


Figure 1. Topology of PFNN

4.2.3. Training Procedure

Initialization step consists of (heuristically) identifying a value for the potential function spread value α and determining a starting configuration for the neural network. Number of nodes in the pattern and output layers is fixed and equal to the dimensionality of the pattern vector and one, respectively. Initially, the hidden layer has one node. The potential function represented by the node in the hidden layer is centered around the location of a randomly chosen training vector. The weight connection from the hidden layer node to the output node is determined based on the class membership of the randomly chosen training pattern. Once the initialization step is complete, supervised training procedure for the neural network consists of the steps in Figure 2.

0. Initialize the PFNN.
1. Present a new feature vector and compute network output.
2. If network classifies the vector correctly,
no action needed.
3. Else (feature vector belongs to the wrong class)
 - a. add a new hidden layer node,
 - b. center the potential function represented by the new hidden layer node around this vector and
 - c. If network output is positive, connect the output of the new hidden layer node to the output layer node using a weight of -1.
 - d. If network output is negative, connect the output of the new hidden layer node to the output layer node using a weight of +1.
4. Repeat the procedure until all training patterns are processed.

Figure 2. Pseudocode for PFNN Algorithm.

4.2.4. Capabilities and Limitations of the PFNN

The PFNN will perform satisfactorily given that the classes are separable and there exists class boundaries of the type defined by Equation 5. Consistency of the training data set where training set is representative of the testing set and does not have conflicting information (wrong class assignment for a particular training pattern) will play an important role for the performance of the PFNN, which is typical for any pattern classification algorithm. A number of theorems related to the convergence properties, the rate of convergence and conditions for termination of the algorithm are presented in the reference by Tou & Gonzalez [1981].

4.3. Probabilistic Potential Function Neural Network (PPFNN)

PFNN generates partition boundaries for pattern classes which are separable. Noise or other real-life imperfections may cause the class sets to overlap in the pattern space and therefore making it impossible to assign a given pattern to a particular class with certainty. In this case, a probability value for class membership of a pattern can be computed to determine the class to which the pattern most likely belongs. The PFNN will be modified to handle the requirements of a stochastic decision making problem. A formal treatment of the problem is presented in the following section.

4.3.1. Mathematical Model^o

Let $p(\omega_i / \bar{x})$ the probability that \bar{x} belongs to the class ω_i , where i is the index for classes. The stochastic decision making rule to identify which class the pattern belongs to is given by

$$\bar{x} \in \omega_i \quad \text{if } p(\omega_i / \bar{x}) > p(\omega_j / \bar{x}) \quad \forall j \neq i. \quad (10)$$

The conditional probabilities employed in the decision rule, $p(\omega_i / \bar{x})$, can be approximated by the following formula:

^o This discussion is an excerpt from section 6.4, Pattern Recognition Principles by Tou and Gonzalez, Addison-Wesley Publishing Company.

$$p(\omega_i / \bar{x}) \approx \tilde{f}_k^i(\bar{x}) = \begin{cases} 0 & \text{if } -\infty < \hat{f}_k^i(\bar{x}) < 0 \\ \hat{f}_k^i(\bar{x}) & \text{if } 0 \leq \hat{f}_k^i(\bar{x}) \leq 1 \\ 1 & \text{if } 1 < \hat{f}_k^i(\bar{x}) < \infty \end{cases} \quad (11)$$

where k indicates the k -th training pattern processed and i is the index for classes. The function $\hat{f}_k(\bar{x})$ can be computed with the iterative formula given by

$$\hat{f}_k(\bar{x}) = \hat{f}_{k-1}(\bar{x}) \pm \gamma_k K(\bar{x}, \bar{x}_k) \quad (12)$$

where the potential function, $K(\bar{x}, \bar{x}_k)$, is as defined by Equation 9 and the coefficients γ_k , $k = 1, 2, \dots$, can be obtained from the harmonic sequence $\{1/k\}$, $k = 1, 2, \dots$, (see the reference for conditions this coefficient must satisfy).

4.3.2. PPFNN Architecture

The PPFNN employs four layers to implement the stochastic decision making rule defined in Equation 10. The first layer of processing consists of nodes in the pattern layer. Nodes in the pattern layer simply distribute the incoming signal values to hidden layer nodes without any weighting. Nodes in the hidden layer loosely represent the cluster centers in the data set and are connected to output layer nodes through modifiable weights, $w_{ij} = \gamma_k^j$, where γ_k^j is the value of the coefficient for training pattern k , hidden node i and output node j . Output layer has as many nodes as there are classes. The fourth and final layer is basically a MAXNET [Pao, 1989]. The topology of the PPFNN is given in Figure 3.

Input layer nodes simply broadcast the pattern values to hidden layer nodes. Hidden layer nodes implement a function of the form $\exp(-\alpha \|\bar{x} - \bar{x}_k\|^2)$ where α is a parameter to set the spread of the exponential function centered at \bar{x}_k . Nodes in the output layer are connected to hidden layer nodes through modifiable weights formed

during training. Output layer nodes sum the in-coming weighted signals and pass the weighted sum through a non-linearity which outputs the actual value of the signal if the signal value is inside the interval $[0,1]$, outputs a 0 if the signal value is less than 0 and outputs a 1 if the signal value is greater than 1. The forth and final layer is a subnet, MAXNET, to choose the node with the highest input excitation value and to set its output to 1, while setting the outputs of the remaining nodes to zero. Each node in the MAXNET layer is connected to only a single node in the output layer without any weighting.

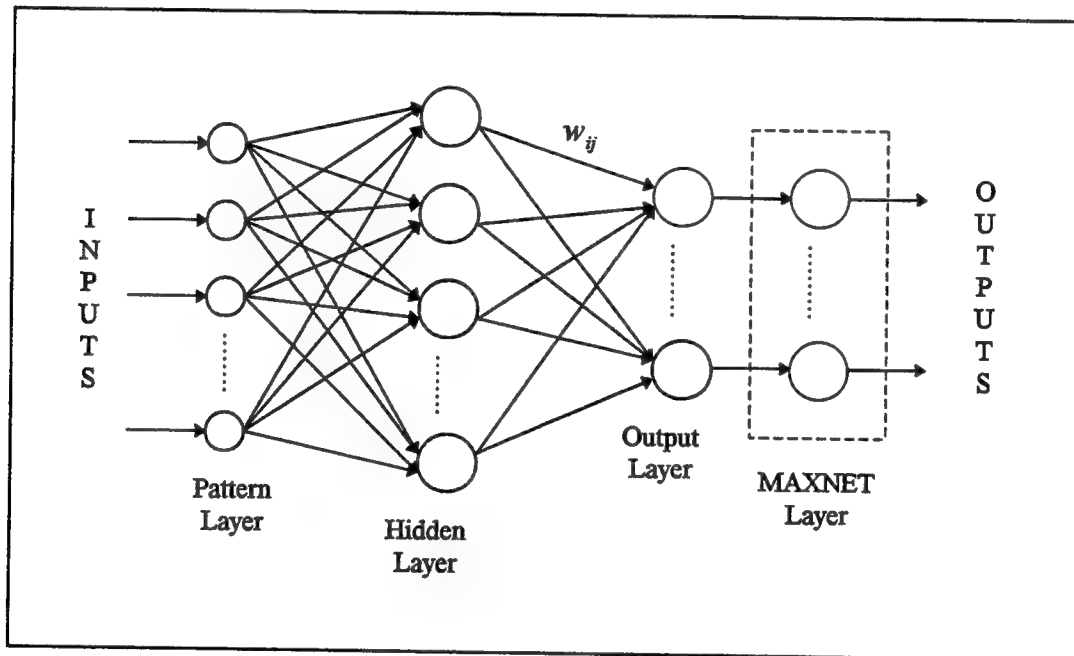


Figure 3. Topology of PPFNN.

4.3.3. Training Procedure

Network parameters to set include α , whose value needs to be determined heuristically based on empirical observations on the actual data set whenever possible, and number of nodes in all four layers of the network. Number of nodes in the pattern layer is equal to the dimensionality of the feature vectors. The hidden layer, initially, will have one node centered around a randomly chosen training pattern. There will be M nodes in the output layer one for each of M classes. Nodes in the output layer are connected to the

hidden layer nodes through modifiable weights, -1 or +1, depending on the class membership of the training pattern. Number of nodes in the MAXNET layer is equal to the number of nodes in the output layer. Each node in the MAXNET layer will be connected to a unique node in the output layer with a fixed weight value of +1. The supervised training procedure for the neural network consists of steps outlined in Figure 4.

4.3.4. Critique of the PPFNN Algorithm

The PPFNN algorithm theoretically holds the promise to satisfy all six design criteria listed in the section titled Introduction. A brief explanation of each criteria and why and how the PPFNN meets that requirement follows next. Training the network requires generating an output for the training pattern and simply adding a new hidden layer node if the network is not able to classify it correctly. Overall training step is straightforward and promises to be very fast. This fast training speed will translate into real-time learning for most applications. The data flows from the pattern layer to the MAXNET layer unidirectionally and computations associated with a specific node in given layer can be performed in parallel with computations associated with the rest of the nodes in that layer.

The initial configuration of the network has one node in the hidden layer. As the training progresses, new hidden layer nodes are added to the network as needed. Note that a tightly packed cluster is likely to contribute one hidden layer node (or a couple more nodes depending on the spread of the potential function as defined by the parameter α) if the cluster center (or any pattern sufficiently close to it) happens to be in the training set. Once a potential function (with proper spread) is placed for a training pattern belonging to a particular cluster, any other training pattern coming from that cluster will be classified correctly by the algorithm and hence, there will not be a need to create a new hidden layer node. The implication is that, on the average, only a small number of hidden layer nodes will need to be created for tightly packed pattern clusters no matter how many patterns belong to that cluster. Therefore, the learning algorithm does have the potential to induce a minimal network topology depending on how well the training pattern set represents the actual class distributions.

The PPFNN algorithm implements incremental learning in the sense that learning does not disturb the existing network topology. Essentially, those parameters computed during earlier learning cycles do not need to be recomputed each time a new training pattern is presented since a new pattern is learned by simply adding a new hidden layer node and associated connections while preserving the existing network topology.

0. Initialize the PPFNN. Assume a value for α .
1. Present a new feature vector (index is k) and compute network output.
2. If the network classifies the vector correctly for each class,
no action needed.
3. Else
 - A. Add a new hidden layer node (index is i),
 - B. Center the potential function represented by the new hidden layer node around this vector, and
 - C. Repeat for each class (index is j)
 - If pattern belongs to the class and function, \hat{f}_k^i , is positive,
no action needed.
 - Else if pattern does not belong to the class and function, \hat{f}_k^i , is negative,
no action needed.
 - Else if pattern belongs to the class and function, \hat{f}_k^i , is negative,
connect output of hidden node i to the output node for class j through a weight of $+\gamma_k^j$.
 - Else if pattern does not belong to the class and function, \hat{f}_k^i , is positive,
connect output of hidden node i to the output node for class j through a weight of $-\gamma_k^j$.
4. Repeat the procedure until all training patterns are processed.

Figure 4. Pseudocode for PPFNN Algorithm.

Identification of an optimal value for the parameter which determines the spread of the potential functions will require an understanding of clustering properties of the training data. This parameter will be correlated to the clustering properties of the training data and

will take a large value if clusters are spread over a large region in the pattern space and accordingly, will have a small value if the clusters are tightly packed in the pattern space. In the worst case, a new hidden node is likely to be created for each training pattern if the value of the parameter α is too small, which will result in a very narrow spread for the potential function, and the training data clusters are spread wide. Even then, the resulting network topology will be no larger than that of the PNN's. If the parameter value is set too large when the actual training data clusters are tightly packed, two or more clusters belonging to two different classes might reside in the subspace where a specific potential function is placed. This is not a desirable situation since the network will not be able to learn the distinction between those two clusters.

5. CONCLUSIONS

Two novel neural network classification algorithms which hold promise to satisfy the requirements of the NREDS classification task have been designed. PFNN is designed for classification tasks where classes are separable and therefore, can be solved by deterministic decision making. The PPFNN is a stochastic decision making algorithm and is designed for classification tasks which have sufficiently large overlap between class distributions. Both neural network algorithms promise the desired properties of fast training and learning, ability to form class partition boundaries for cases where classes are multi-modally distributed and formed from a set of disjoint pattern clusters, dynamically adapt its topology during training to the requirements of the particular problem, learn from a minimal number of training patterns, and approach the performance of the theoretical Bayesian classifier.

Performance evaluation of both neural network paradigms for a set of classification tasks including the NREDS task still remains to be done. The follow-up research effort will consist of verifying the theoretical promise of two algorithms using computer simulation studies on actual NREDS data sets.

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**Implementation of Artificial Intelligence in Air Force
Printed Circuit Boards Test**

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**Final Report for:
Summer Research Program
San Antonio Air Logistics Center**

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ARTIFICIAL INTELLIGENCE IN AIR FORCE PCB TEST

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Abstract

In this research, we investigated the implementation of Artificial Intelligence (AI) in automatic testing of Printed Circuit Boards (PCBs). Five major AI tools have been considered for this implementation: Fuzzy Logic, Genetic Algorithm, Artificial Neural Networks (ANNs), Hybrid Artificial Neural Networks, and Expert Systems (ESs). Three major types of automatic tests have been considered; they are: Depot testing, Signature identification testing, and X-ray and electromagnetic testing. For each test we assigned the most efficient AI tools and recommended the way the test should be conducted. The finding of this research will be implemented as a road map for the Air Force in investing in AI for automatic test.

Introduction

Implementing Artificial Intelligence (AI) in Printed Circuit Boards (PCBs) automatic test has three potential benefits: a) enhance the performance and reliability of the test equipment (b. lower down the cost of testing, and c) allow for accurate field test. The task for this summer research was stated by the SA-LCA/LDAE Kelly Air Force base as follows:

"There have been many attempts, with varying success, to apply artificial intelligence techniques to automatic test. Expert systems, neural networks, fuzzy logic, genetic algorithms and other flavors of AI have been tried. Applications have included the extraction of test requirements and strategy from product design data, image processing (IR, X-Ray and electromagnetic fields) and pattern recognition, circuit diagnostics and dynamic test resources allocation. The DoD has invested in new technologies, sometimes using the AI "hot topic" of the month rather than carefully matching the problem to the right algorithm or approach. What is needed is a document that identifies the applicable AI fields with their strength and weakness, and matches them to the opportunities for improving the test process. This view should encompass the entire product cycle, from using design data to develop automatic test to the application of automatic test in the depot. Related programs and standards should be allowed for, such as AI-ESTATEs (Artificial Intelligence and Expert System Tie to ATE.), which is an IEEE standards program. The end result of this study should be a document that will serve as a road map for the Air Force in investing in AI for Automatic test. "

To achieve the above goals, I have done the following: a) reviewed more than 100 major papers in the field of automatic testing and artificial intelligence, some of them are shown in the reference section [1-9], b) investigated all the major types of tests at ALC- Kelly Air Force Base, c) participated in a meeting at Kelly Air Force of national and international researchers in the field of AI in automatic test; their major suggestions are included in this report, and d) attended a special tutorial seminar on the Air Force Automatic Test Equipment.

The prospective AI technique should have the following characteristics: a) yield high diagnostic/test performance, b) easy to use (user friendly) c) use as much as possible of the existing test concepts d) universal as much as possible e) easy to upgrade.

Major Tests That Have Been Considered

Three major tests have been considered in this study, they are:

1. Power Supply Test (Depot Test) It is done by coupling the power supply to a large test equipment (Advance Power Supply Tester) that provides stimuli. With the aid of test programs, the power supply is tested. The test is done sequentially component by component. Any complex component such as a microprocessor is tested by examining its behavior to simple input patterns. The test equipment is large and is designed to test specific power supplies. The test is fairly accurate.
2. PC-Board Test (Depot Test) It is done by the aid of a large Tester (such as GENRAD) that supplies stimuli through a test/diagnostic program. The circuit is usually simulated to identify the test patterns. The test equipment is huge and the test depends on the function of the components of the board. The test takes a long time to be completed but it is fairly accurate.
3. Signature identification Test: This test is done by signature capturing devices such as the Huntron Tracker or the Scorpion. The device injects signals (sine wave signals) into the pins of a populated, unpowered boards and then captures the response of these signals. This device is employed by the Air Force and the Navy. The Capturing of the signal is done automatically by a probe attached to a camera; the movement of the probe is carried out by a motor. The concept here is that the response of the pin to this stimuli is different when the pin is shorted, opened, or loaded with other components. By analyzing the response, the operator may know whether the board is bad or good and which component is faulty (if any). The main features of the device are:
 - a. The captured signals from any component are independent of the function of the component.
 - b. The device is compact, low cost (under \$ 20K) and PC-based; the AI algorithms can be stored in the PC.

- c. It may allow for fault insertion. If a model describes the captured signal in terms of the type of faults is developed, then faults can be simulated and their captured signals can be learned.
- d. The board under test is unpowered
- e. The performance of the device is relatively low.

4. Tests under Development or in Research Stage: Two tests are considered here: the X-ray imaging and the Electromagnetic imaging. The Electro Magnetic (EM) imaging test captures the electromagnetic field of the current passing through the components of the PCB. The concept here is that a good board will display different EM pattern than the bad one. The board has to be well-shielded from any external objects that may affect the EM pattern, also the ability to differentiate between the patterns of good and bad boards has to be investigated. This test is in the research stage. The X-ray imaging test: is based on capturing the X-ray pattern (image) of the PCB; the test is currently under development to detect mechanical failures such as bad traces and soldering joints. The concept here is that image of the X-ray pattern of a good trace (joint) is different from that of a bad trace(joint). This research is under development by a private contractor (CMI) of San Antonio, Texas.

In the following sections we discuss different AI tools that can be implemented in the above tests. Details of these tools can be found in [1], [2], [4], and [6].

A. Fuzzy Logic

A crisp set is a normal set that has definite boundaries. A fuzzy set is one in which the boundaries of a crisp set have been skewed. In a tradition fault diagnosis, the test result is expressed as: yes or no, 0(bad) or 1(good), failed or passed. The fundamental idea behind the theory of fuzzy sets is based on the observation that human thinking is not just two-valued but logic with fuzzy truths. A fuzzy set, A, for a set of objects $X = \{x_1, x_2, \dots, x_n\}$ is defined as a collection of ordered pairs: $A = \{(x_i, m_i(x_i)), i = 1, 2, \dots, n\}$

The entity $m_i(x_i)$, a real number in the interval $\{0,1\}$, is called the membership function. It is used to represent the membership grade of x_i in A. A subset of objects in X with positive values of membership function, $m_A(x_i)$, is called the supports of A. A value of one for $m_A(x_i)$ indicates that x_i does belong (or completely in) A; a value of zero indicates that x_i does not belong to A. A value between zero and one indicates partial membership. Expressing the membership function in a fuzzy set is still one of the main subjects of debate. Triangular-shaped, see figure 1, or Euclidean-based functions are usually used to express the degree of membership in a fuzzy set.

It is desirable to apply Fuzzy logic to PCB test since the output of the logic expresses the result of the test in fuzzy terms such as very good, very bad, bad,..... or 90% pass, 50% failed, etc.. instead of crisp results such as good or bad.

B. Genetic Algorithm

Genetic algorithms (GAs) are a very powerful new technology for searching for solutions to difficult problems. They mimic the reproduction and evolution process in human where the best fit individuals are those who will survive and produce offspring. Hybrid Genetic Algorithms and Neural Networks provide an advantage whenever input patterns are very noisy; and potentially small improvements in performance can result in substantial advantage in resource allocation.. From an engineering prospective, this new paradigm is a very powerful method for searching through a large solution space. Every

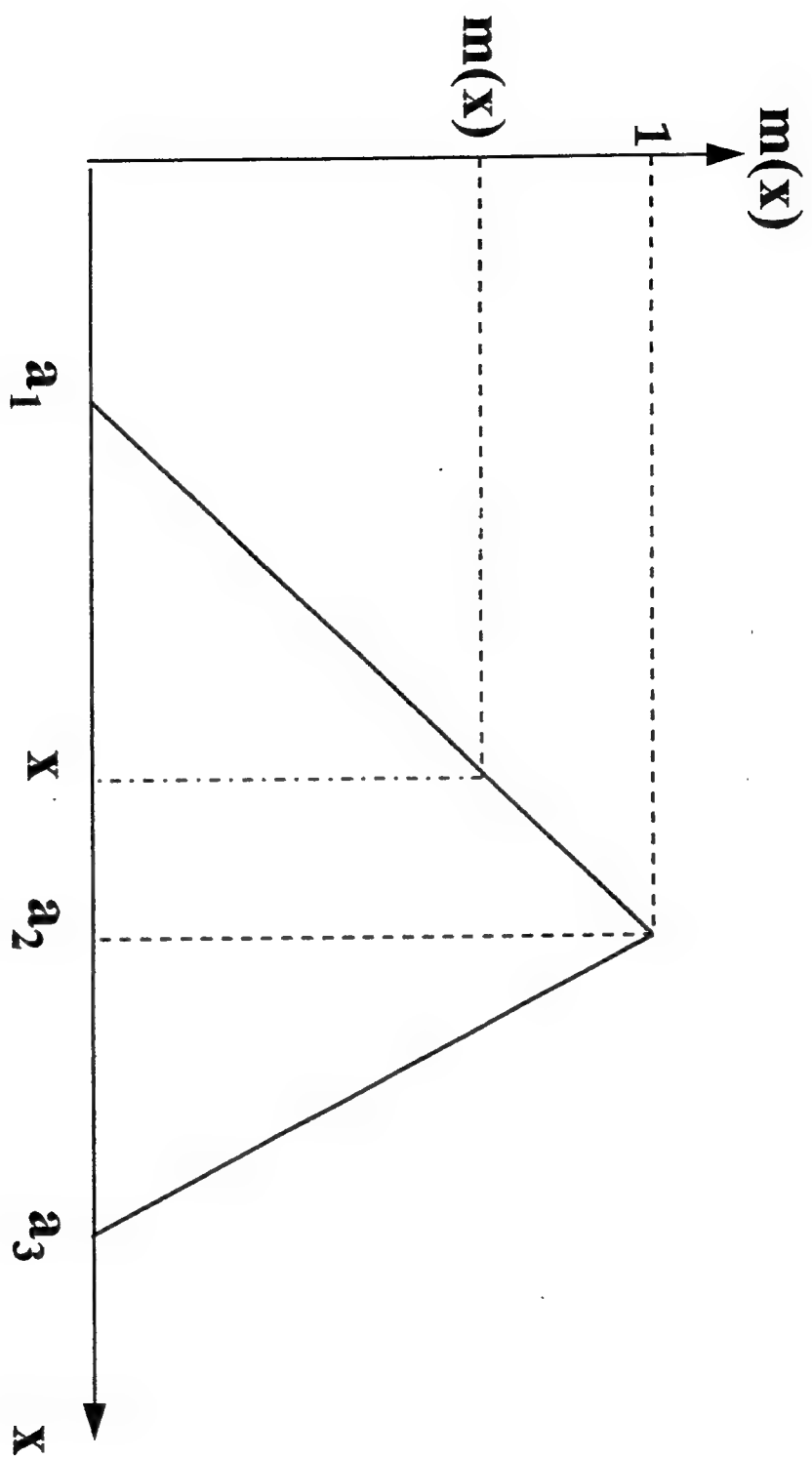


Figure 1.

GA problem must first be formulated as an optimization problem. The form of the problem is that there is some universe of possible solutions, and the objective is to maximize a specifically chosen objective function. This is known as a fitness function.

Genetic algorithm can be performed as follows

1. Encode the decision variables as a chromosome
2. Initialize a population of chromosomes as the current generation.
3. Perform the following iterations until a stopping criteria is met:
 - a. Evaluate the objective function (fitness)
 - b. Select some chromosomes in the population with the higher fitness as parent chromosome to produce a new generation
 - c. Apply crossover and mutation to the selected chromosomes
 - d. Replace the entire population by the children chromosomes as the current generation.

Artificial Neural Networks That can be implemented in Automatic Test

In the AI domain there are two major tools: Expert System (ES) and Artificial neural Networks (ANNs). Other tools such as Genetic algorithms and Fuzzy logic can be used as separate tools or can be combined with the above tools. Each tool has its advantages and limitations.

Figure 2 shows a block diagram of the test technique using artificial neural networks. The feature extraction is the process where parameters (features) are extracted from the test procedure. These parameters can be voltages, currents or signals from test points on the PCB. The extracted parameters are applied to the input of the Artificial Neural Network (ANN). The output of the network is a diagnosis of the condition of the PCB. Artificial Neural Network consists of a system of interconnected processing elements. The function of the network (classification, pattern association, prediction, optimization, ...etc..) is governed by its topology. Artificial Neural Networks are best utilized when the input information to be processed is incomplete, noisy, or ambiguous. The network allows real-

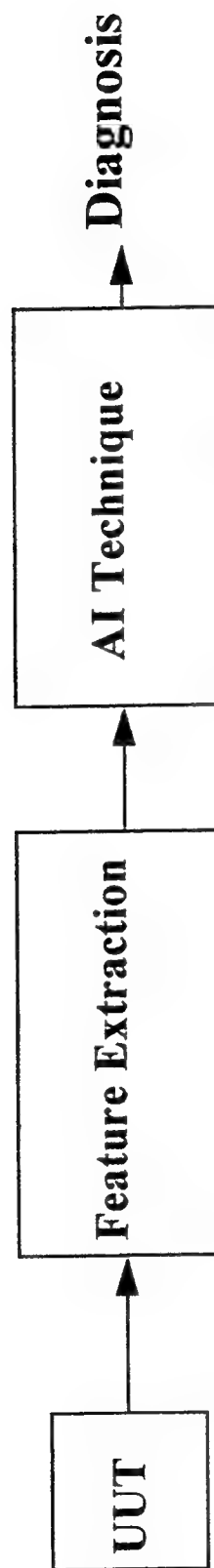


Figure 2.

time processing due to its large number of processors. A distinguish feature of these networks is that they can "learn" from previous examples.

Figures 3,4,5, and 6 show a multi-layer perceptron, Hopfield, Kohonen, and Recursive neural networks respectively. Also shown in each figure the advantages and limitations of each network.

In the following we discuss some of the hybrid artificial neural networks. Hybridization is between the network and either fuzzy logic or genetic algorithms.

G. Hybrid Recursive -Fuzzy ANN

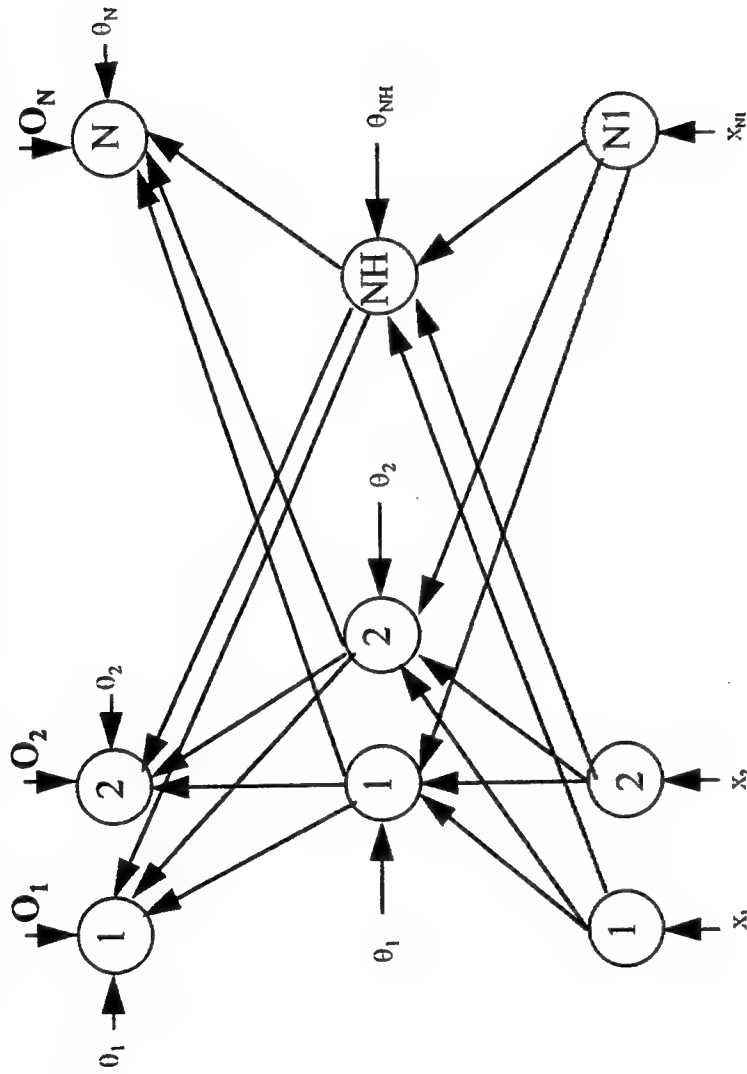
The fuzzy neural network classification algorithm consists of two stages. The first stage is an unsupervised recursive neural network classification process. In this stage, the algorithm classifies the training instances into a certain number of clusters determined dynamically. The topology and weights of the network are adjusted according to the training instances. After all the training instances have been classified, the values of the mean vector for each cluster are stored in the weights associated with the links between the input and output nodes.

The second stage is a fuzzification process. In this stage, the fuzzy membership values for each training instance in the set of supports, classified clusters, are evaluated. Figure 7 illustrates the algorithm

H. Hybrid Genetic ANNs

The results of neural network training are sensitive to the initial value of the weight vector. A genetic algorithm can be employed to perform global search and seek a good starting weight vector for the subsequent neural network training algorithm. The result is an improvement in the convergence speed of the algorithm. Also the problem of entrapment in local minima is circumvented by using the genetic algorithm which is guided by the fitness function of a population rather than a gradient direction.

C. MULTI-LAYER PERCEPTRON ANN



BackPropagation Training Procedure-supervised

simple-static topology

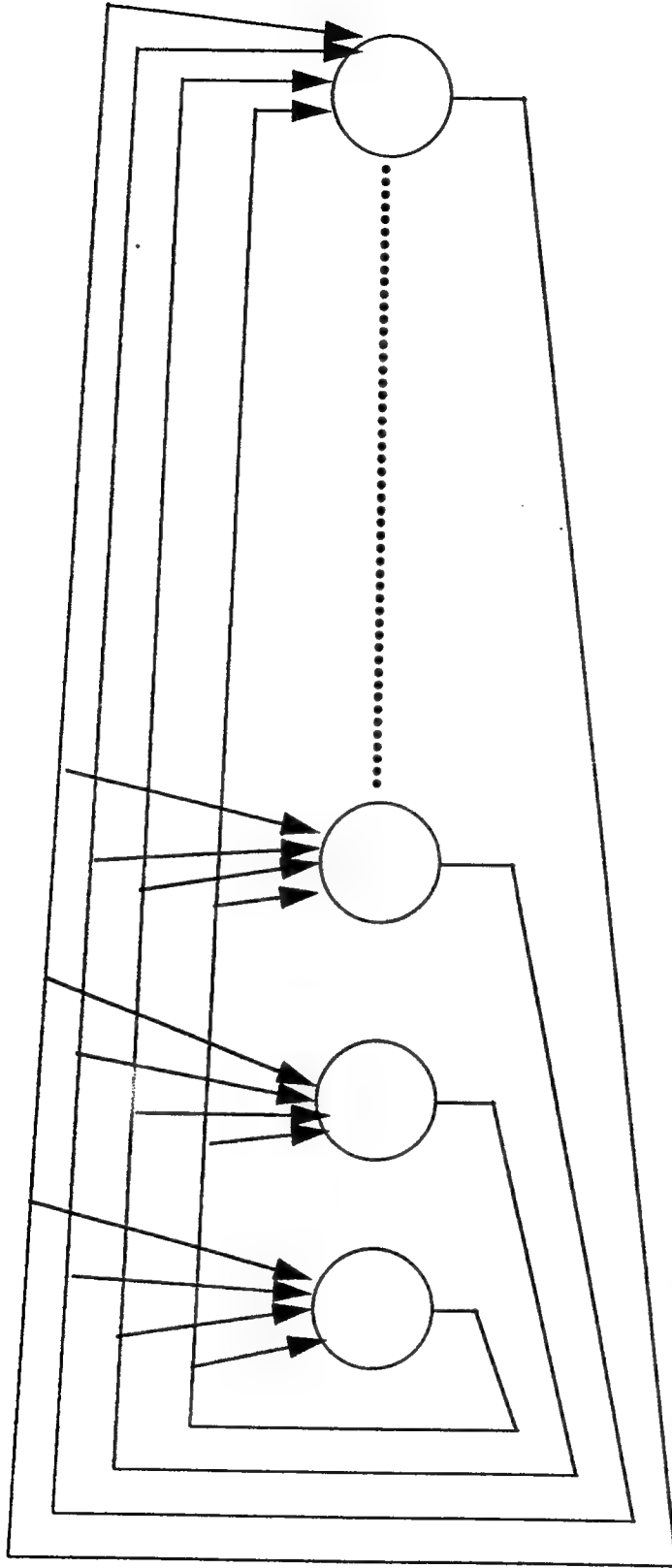
Classifier (Crisp)

Local Minima

stationary

Figure 3.

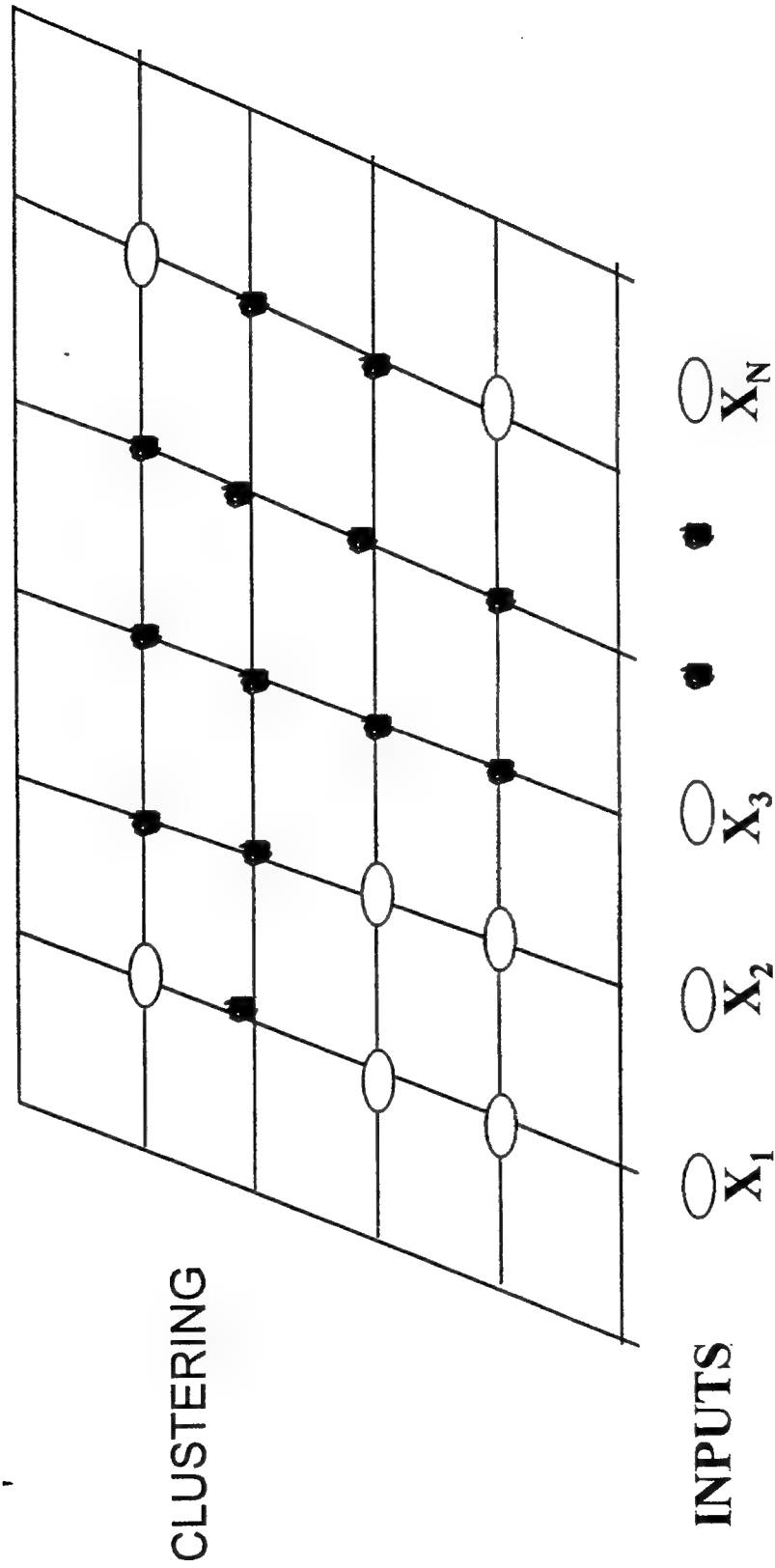
D. HOPFIELD



Fixed weights-Hebbian rule training
Binary
Associate memory-classification(crisp)
Storage limitation $.15 N \approx M$
Stationary

Figure 4.

E. KOHONEN NEURAL NETWORK



Unsupervised
Clustering
Kohonen learning rule

Figure 5.

RECURSIVE-Cont.

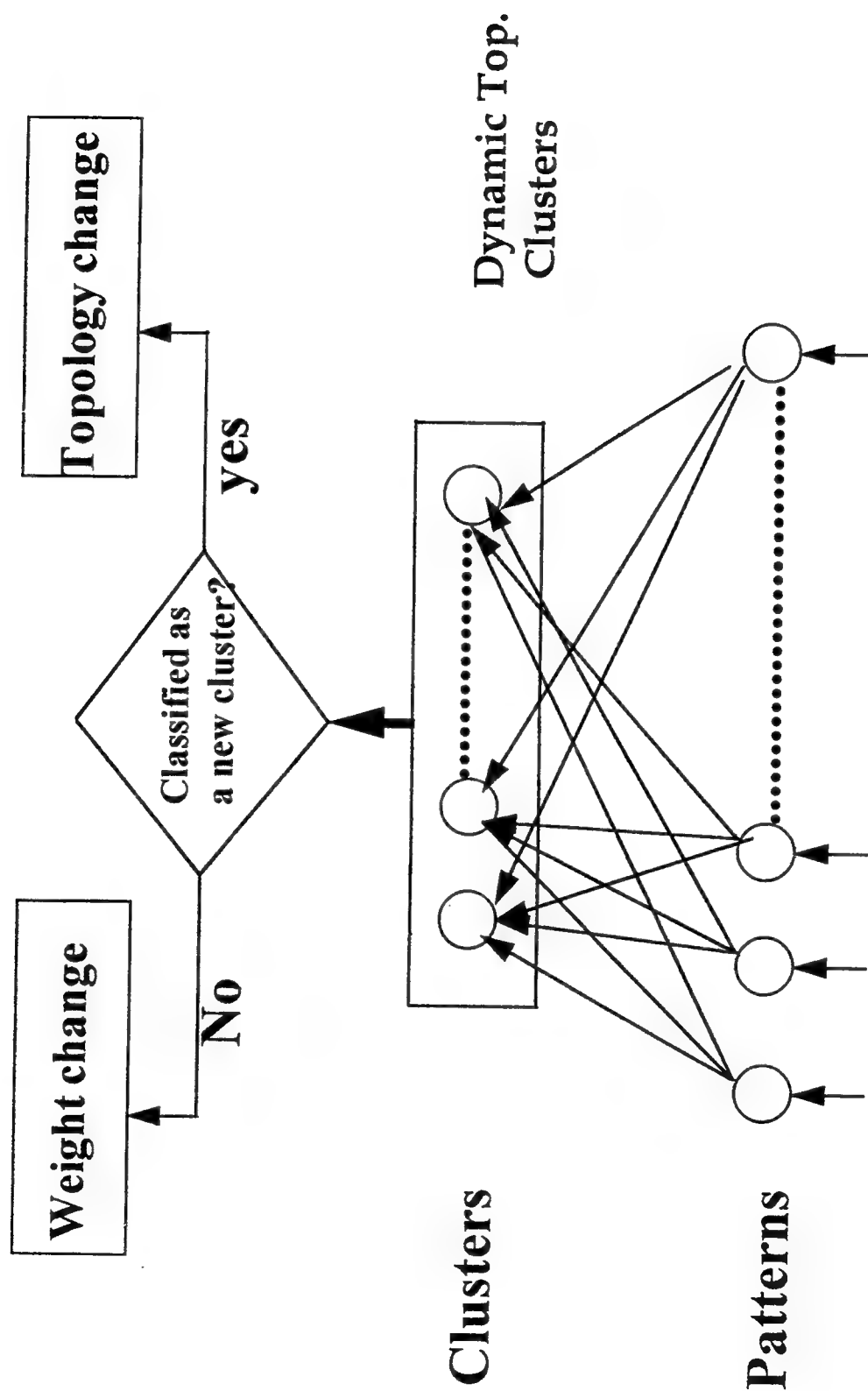


Figure 6.

UNSUPERVISED-CLASSIFICATION-FUZZIFICATION

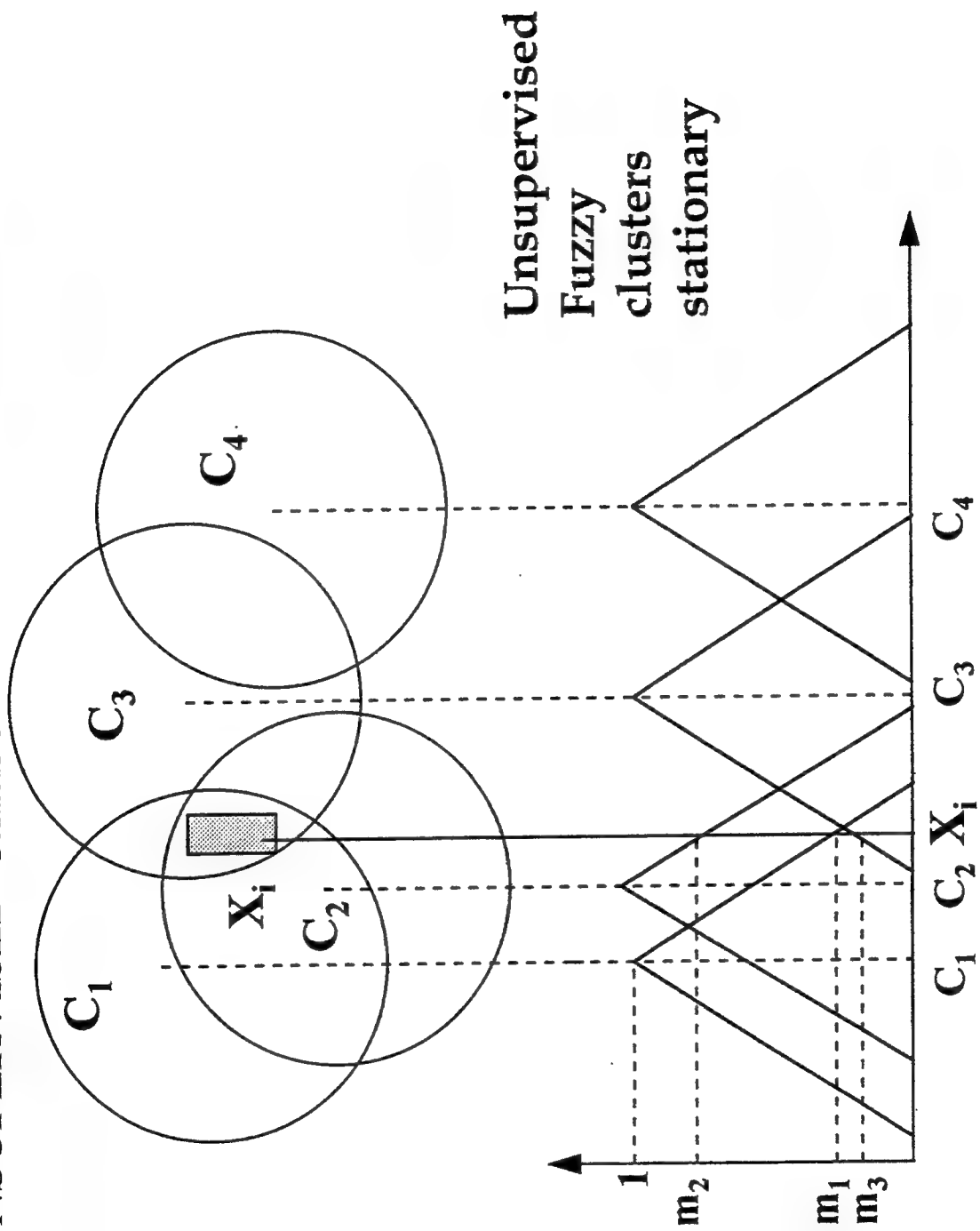


Figure 7.

I. Expert Systems

Model-based Expert systems apply a qualitative or numerical simulation of the problem domain to the diagnostic process. These systems reason on the basis of physical principles, and therefore are capable of performing diagnoses for a wide range of inputs. However, simulation models are usually too slow to be effectively applied in real-time environment. Also, Knowledge acquisition is a problem area shared by both rule and model-based expert systems. Rule bases must often be tediously hand-encoded and are not suitable for representing non-causal knowledge. The development of reliable simulation models is also generally a difficult and time-consuming process. Expert systems are best utilized when the input information to be processed is complete, well defined, and not in need for fast processing. However they lack the "Learning" ability.

The following table shows the four tests that we have considered in this study, the suggested Feature Extraction (FE) method, AI tool to be implemented, and the training procedure if artificial neural network is selected.

Test#	Suggested FE	Suggested AI	Training Procedure (if ANNs is selected)
1	Signals from test Points	A,C,F,G,H,I OR combination of I and either A, C,F,G, or H	Simulation-FI or training instances
2	Signals from test points	Same as above	Same as above
3	pin's signal signature	E,D,G, or H	Modeling-FI or training instances
4	morphological, image,etc.. Needs extensive study to determine the correct features.	E,G, or H	Training instances or modeling if possible

FI = Fault Insertion

General Recommendation and Discussion

1. The artificial neural network technology has been matured over the last few years. All the paradigms presented here and many more are available as commercial packages or in the public domain. The user can implement a variety of paradigms without the need to write their codes.
2. For test 2 where extensive simulation and test codes are usually done, ES and ANNs can be combined to perform the diagnosis. ES takes advantage of the available data base and the ANNs can be applied to solve any ambiguous patterns such as complex analog patterns.
3. Implementing AI technology on Test #1 and #2 should be done step by step since it will be necessary to make extensive changes to the operating system of the test equipment to accommodate the AI. It is recommended to apply the AI on prototypes or simple boards, before applying it on the actual equipment, to show their feasibility.
4. Test #3 is a potential target for implementation of ANNs. The way the signal is injected and captured automatically is very suitable for ANNs implementations. This test can be a model to show the effectiveness of the networks. Lack of training data can be solved by fault insertion or by using unsupervised adaptive networks.

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Use of Statistical Process Control in a Repair/Refurbish/Remanufacture
Environment with Small Lot Sizes

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**USE OF STATISTICAL PROCESS CONTROL IN A
REPAIR/REFURBISH/REMANUFACTURE ENVIRONMENT
WITH SMALL LOT SIZES**

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Abstract

The repair/refurbish/remanufacture environment of the repair depot at Kelly Air Force Base is a non-traditional manufacturing operation aimed at the maintenance of the Air Force's aircraft. Since maintenance of used aircraft entails the disassembly of the aircraft and components of the aircraft, inspection of the parts for wear replacement or repair, refurbishment and reassembly, testing, and return to the users, the variability of the functions necessary to repair the aircraft is high. With small lot sizes, high variability of the work load, and long cycle times, traditional use of statistical process control is very difficult or inappropriate. The assessment of statistical process control in this unique manufacturing environment was the aim of this project.

The use of statistical process control in the San Antonio Air Logistics Center was investigated as to the present use of the discipline as of the summer of 1995, the appropriateness of that present use, the correctness of the present use, the potential use of traditional statistical process control techniques, the potential use of non-traditional statistical process control techniques, and the areas where the use of statistical process control is not recommended.

Five directorates in the facility were investigated. The use of statistical process control was almost non-existent at the time of the project. Potential implementation areas for statistical process control are enumerated for each directorate, the various techniques for non-traditional use of statistical process control are identified with the areas for potential use, and the proper sequencing of the implementation of the statistical process control techniques for small runs, attribute charting, and variable charting are given.

The impact of statistical process control at Kelly is discussed in relation to defense downsizing, the Base Realignment and Closure Commission, and privatization at Kelly Air Force Base. Conclusions and recommendations are included.

USE OF STATISTICAL PROCESS CONTROL IN A REPAIR/REFURBISH/REMANUFACTURE ENVIRONMENT WITH SMALL LOT SIZES

Roger G. Ford, Ph.D., P.E.

1.0 Introduction

1.1 Source and Task

The Air Force Office of Scientific Research (AFOSR) 1995 Summer Faculty Research Program sponsored the research topic: Use of Statistical Process Control in a Repair/Refurbish/Remanufacture Environment With Small Lot Sizes. The research was carried out at the San Antonio Air Logistics Center (SA-ALC) at Kelly Air Force Base, San Antonio, Texas, during the months of May through August. SA-ALC has the responsibility of providing Programmed Depot Maintenance on aircraft and repair, refurbishment, and/or remanufacture of aircraft and auxiliary power engines and components. Parts in need of refurbishment due to wear and age are remanufactured in a job shop, small lot size environment as needed.

For a period of six years, SA-ALC has been implementing Total Quality Management (TQM) concepts and the associated use of metrics in appropriate areas. Statistical Process Control (SPC) is one of the methods of analysis associated with TQM and high volume output in a manufacturing environment. But at the ALC, due to its unique atmosphere of repair/refurbish/remanufacture and the high variability of tasks associated with maintenance of aircraft, SPC is widely believed to not be applicable in this environment due to the low volume, small lot sizes, long cycle times, and high degree of variability of tasks performed.

The application of SPC insures processes are in statistical control, essentially predicts when the processes will be out of control in the future if measures are not taken, identifies rare occurrences of problems and triggers identification leading to solution and prevention of reoccurrence, reduces rework dramatically and the high costs associated with it, and raises the quality of the final product, in this case high performance aircraft with pilots' lives, passengers' lives, and expensive equipment at stake. It should be noted that the output of SA-ALC has always been of high quality. A problem arises when cost of rework and cost of delays is considered. The very efficiency of the operations at SA-ALC is the focus of SPC implementation as well as capability of the processes involved.

In any environment, care must be taken to insure proper application of SPC theory. Mistakes have been made and are being made in industry as a whole in the application of SPC to inappropriate situations, making the wrong choices concerning applying variable or attribute charting techniques, not fully understanding the statistical theory behind SPC, going through the motions to satisfy corporate demands, and others. The careful selection of pilot SPC studies and research efforts at SA-ALC needed to be made to be sure that the credibility of SPC techniques was maintained. Training of the people involved at all levels from the shop mechanic to the Director needed to be accomplished before acceptance, much less success, of SPC could be realized. The five main directorates within SA-ALC that perform the actual repair/refurbish/remanufacture tasks were investigated. The

investigations dealt with the current use of SPC and whether that use was being performed correctly, identifying the areas where SPC could be applied successfully and the procedures involved in that application, and the limitation to the use of SPC and infeasible situation areas.

1.2 Traditional Versus Non-Traditional SPC

1.2.1 Misconceptions

Statistical Process Control (SPC) is essentially a method to confirm that the correct process has been selected for a product or set of products and that the process is being controlled in such a manner that it consistently produces finished parts that comply with the designer's desired dimensional targets. The ideal time to implement SPC is before the very first product's raw material is set-up on a machine. To use Juran's Trilogy of quality activities - planning, control, and improvement - planning on the proper choice of equipment for a particular manufacturing activity should come first. In the case of this study at SA-ALC, however, the products and processes are already in-place. Gaining control or simply the knowledge of whether the processes are in control or not is step one.

The traditional application of SPC techniques is generally thought to be in the original production of parts in quantities of hundreds or thousands. For example, a company makes widgets of three sizes and the demand is high for all three sizes. Therefore the scheduling department says that the four machines making widgets will be producing all three sizes at all times by doing size one on machine A with an output of one thousand per shift, size two on machine B with an output of six hundred per shift, size three on machine C with an output of five hundred per shift, and machine D will be changed on a monthly basis to accommodate the demand. Here is a virtual continuous production utilizing the same process where samples from each machine can be easily drawn for measurement of critical machining parameters each shift. Variable charting is used when there exists at least ten different values for a critically measured parameter and repeat values make up no more than 20% of the data set. Then SPC variable charting can be easily done for control of the process. If that criteria for the data set is not met or there are no measurements, only defects or good/bad determinations made, then attribute charts are possible. Attribute charting is done when the data that exists is in the form of non-conformities per unit, defects per unit, defective welds per unit, number of cracked rivets per panel, etc.

At SA-ALC, the repair/refurbish/remanufacture environment means that there are no situations like the example above. The processes are exposed, with a few exceptions, to small lot sizes, long cycle times, and a high variability of the product mix depending on the need. Traditional SPC is not useful. But, there are many short run SPC techniques for variables available such as moving range charts, charts for individuals, multiple readings SPC, CuSum charts, the exact method, code value charts, and stabilized control charts for variables. Also, many people do not realize that attribute charting is a very useful method for gaining control and for highlighting problem areas for further study.

1.2.2 Concerns with Implementation of SPC

In many cases, the implementation of SPC comes in a direct relationship with an executive having attended a four day seminar on Total Quality Management. His brief exposure at this seminar to SPC has led him to dictate to his people that SPC will be implemented in all areas in his plant. The result of this approach to SPC implementation is disastrous because no one really knows the basics of SPC, and they are simply going through the motions for their boss.

Another wrong approach to the implementation of SPC is to start the implementation in a bottom-up, comprehensive manner. This scenario usually results from a manager or top executive familiar with SPC and its benefits but not empathetic with the response of the workers to a new concept. SPC, simply because it has the word "statistical" in it, is frightening and confusing to most unexposed individuals regardless of their position. An executive must realize that the implementation of a new and difficult to understand technique takes time for training, exposure, and use.

A blanket implementation approach by either the first "uninformed" scenario as mentioned previously, or through an informed, sincere desire to implement SPC company-wide without regard to the impact it will have on employees is not going to be successful in most cases. If personnel do not see a direct and immediate benefit in the technique, confidence will be lost and the feeling of "why are we going to all of this trouble for a bunch of fancy charts" will prevail.

The preferred approach to implementation of SPC techniques is a careful examination of the problem areas that exist, the choice of a pilot study area that will provide fairly quick and needed information on a procedure or process, the training for all involved personnel so that the impact of the SPC application is understood, the proper design of data gathering techniques, data analysis techniques, and charting procedures, and the on-going evaluation of existing conditions and associated problem area resolution. Upon completion of a successful pilot SPC implementation, confidence in the technique will have grown, further areas for SPC implementation will probably have been identified, and support for the on-going SPC effort will be established. The eventuality of this preferred approach will be full SPC implementation in the areas that are in need of it the most first and in the proper use of SPC techniques, interpretation, and evaluation.

As an example, the LD Directorate repairs and refurbishes jet fuel starter (JFS) and central gear box (CGB) components for the F-15 engines among many other items. The items arrive at SA-ALC, are disassembled, the parts cleaned, inspected, routed to repair shops or discarded to be replaced by new purchase, accumulated in stores, kitted, assembled, and tested. As part of this project, the choice of where to apply SPC in LD was very important for the reasons mentioned above. With full cooperation of the LD management, engineering, and shop personnel, a pilot SPC project was implemented in the JFS and CGB assembly areas. The reason for this choice was to highlight: first, whether there were problems associated with the final assembly of the components due to rejects, delays, wrong parts kitted, etc.; second, what repair or purchase areas and specific part numbers needed further investigation so as to reduce rejects and delays at the final assembly point; and third, to determine if the final

assembly of the JFS and CGB components was in statistical control. The next steps from this pilot study should be in-depth investigation into the areas and parts found to be problems in final assembly. (Refer to the LD Directorate findings for the results of this pilot study.)

On a final note, it should be mentioned that SPC is not reserved for the manufacturing environment. There are many applications in the service arena and administration efforts where paperwork can be evaluated as to its correctness in completion, the number of days in completing assigned objectives per task, man-hours per project, etc. Most people assume that SPC is only for operations where metal is removed by machine tool. This is not the case, and applications of SPC should be sought where some of the above mentioned situations arise.

1.2.3 Use of SPC in Non-Traditional Applications

The most important part of any SPC application is the gathering of the data that is needed for analysis. In many cases, proper metrics such as the "Seven Tools" are not being attempted. The management control from just Pareto analysis charts or run charts is tremendous. The intelligent use of metrics is being promoted at SA-ALC, but there are many areas where even metrics are not being done.

One of the arguments against the use of SPC at SA-ALC is that there is virtually 100% inspection of parts before final assembly or test. The problem with this attitude is that even 100% inspection does not provide any information on the process such as trends, unusual occurrences, or control information. In fact, it has been shown that 100% inspection is really only 85% effective, meaning that there are errors in inspection of both type I and type II or good when really bad and bad when really good. Inspection would yield a 15% inefficiency (85% efficient) by itself when SPC techniques give control potentials of $\pm 3\sigma$ or 99.73% efficiency (0.27% inefficient).

Another argument against the use of SPC is the short run, low volume, high variability of the nature of production at SA-ALC, which is fairly unusual, especially in such a large magnitude. The recommended method to control short production runs is to control the process instead of the product. If a machine, for example, works on many different parts in a week's time, careful choices of individual axes measurement of critical part parameters on each part will enable SPC charting of deviation from target dimensions on each part. The charting will then yield information on the machine itself as to its capability to perform as to variation from the target measurements and in determining trends for control of the process in the immediate future.

As mentioned previously, there are many short run SPC techniques for variables available such as moving range charts, charts for individuals, multiple readings SPC, CuSum charts, the exact method, code value charts, and stabilized control charts for variables. These techniques are easily found in textbooks but care must be taken in the specific application of these techniques due to their need for understanding of the statistics behind their use.

In the absence of traditional SPC applications (of which there are a few at SA-ALC) and the inability to apply non-traditional or short run SPC techniques, the use of attribute charting is recommended. Attribute charting allows the control charting of data on defects per unit. This kind of SPC application is much easier to understand and to train when most personnel are essentially unexposed to the concept of SPC. A good approach to SPC application is to start with proper metrics, then move on to attribute charting, and finally, when confidence in the

SPC concept is established, the use of variable charting. By this progression, the acceptance, success, and belief in SPC will have success in implementation.

1.3 Cost Accounting in the Air Force

Cost accounting is the inevitable result of a manufacturing enterprise interested in knowing what their manufacturing operations cost and the impact that rework has on the bottom line. The same holds true for the Air Force, but not in the same way that it does in private industry.

The eventual customer of the repair depots like Kelly AFB is the individual wing commander who has responsibility of the aircraft being repaired or refurbished. Until approximately two years ago, repair costs to aircraft and the control of the money to pay for such repairs was centralized at Wright-Patterson AFB. Then, the cost of repair and the control of that money was de-centralized out to the individual using commands. This change focuses the control of repair costs on the end user enabling tighter control and more decision-making ability at the aircraft's usage point. A wing commander now has the option of repairing in-place, if that is indeed possible, or send the aircraft, or part of the aircraft in need of repair, to a repair depot.

Now, here is where private industry and the Air Force still differ somewhat. If the item to be repaired is a sub-assembly to a jet engine, for example, the wing commander will be charged a fixed rate for the repair regardless of the cost of possible rework incurred. The quality of the work is not in question, since SA-ALC has an impressive record of high quality repair. But, the repair work is done with however many rework cycles are necessary to be sure of a working, high performance product. Rework and delay costs have not been a major concern. They were simply factored into the fixed costs of the components produced and charged accordingly. Over a period of time of a year or more, those fixed costs could be adjusted up or down depending upon the performance of the repair facility. Therefore, eventually, unlike in private industry where such costs must be accounted for immediately, the costs of excessive rework and time lost to part delays will be passed on to the wing commander. Until the costs catch up with the user, the repair facility suffers the increased cost due to excessive rework as overruns.

All of this, and especially the fact that the cost of repair and the associated cost accounting is becoming increasingly the responsibility of the aircraft's user, means that it is in the best interests of the repair depot to gain maximum control over their processes in order to reduce time delays and costly rework to the items that they repair/refurbish/remanufacture. By doing so, their costs to return items to use will drop and the incentive for the wing commanders to continue to send parts for repair without overrun costs will be in place.

1.4 Outside Factors Affecting SPC and Efficiency at Kelly in the Summer of 1995

1.4.1 Downsizing of the Air Logistics Centers

There has been pressure on the Air Logistic Centers over the past few years from the Air Force, the Department of Defense, and the Congress to downsize due to the expanding national debt, the end of the cold war, and the trend of continuing annual federal budget deficits. This has meant a gradual reduction in the workforce at Kelly over the last several years. That pressure to downsize is known to be continuing in 1995. The actual effect on the number of employees at the Center over time may fluctuate due to the dynamic nature of the operation of the ALCs and new aircraft coming on-line like the C-17. But the overall trend will be down.

The use of SPC is a tool in which efficiency of a process is determined and the identification of excessive reject and rework is identified. If reject and rework can be identified and the process involved brought under control through the use of SPC techniques, then reductions/reassignments of affected personnel can be a result. This could aid in the downsizing effort and requirements.

1.4.2 Base Realignment and Closing Commission (BRACC) and Privatization

The most current efforts by the BRACC have resulted in the official realignment of Kelly AFB. The ALC will have until the year 2001 to close its present operations. The direct effect will be on the 11,000 civilian employees at SA-ALC. This can be done in two major ways. Current operations can be transferred to other ALCs on an individual basis according to the capacities of the remaining three ALCs. Certain operations can be "privatized in-place", meaning that private industry can bid to do the work presently being done by SA-ALC on an individual operation basis in the same location with pretty much the same employees. Or, there can be a combination of the two approaches.

It needs to be emphasized that SPC usage is promoted by the ISO 9000 standards, and private companies interested in privatizing operations at Kelly may be looking for the use of SPC to verify quality performance from the personnel and operations before bidding on the work. The very future of many employees at Kelly depends on the impression that the work that they do is of high quality and needs little to no rework. The profit motive in the privatization effort from outside private companies means that they expect very low to non-existent reject rates and costly rework. Having SPC and the process control that it can bring through the proper application, installation, maintenance, and evaluation/use could enhance the appeal of Kelly operations to private industry and the privatization effort.

A paradoxical situation has arisen at SA-ALC with relationship to the BRACC action of June, 1995, downsizing of the size of repair functions in the Air Force, and the hope of "privatization in-place" of as many present operations as possible to retain jobs. Downsizing and the BRACC action are large factors on lowering morale of the workforce at SA-ALC. When either blue collar or white collar workers' morale is low, the incentive to instigate a new statistical, complicated analysis tool such as SPC requiring in-depth investigation and focus would not be high on the list of things that they want to do. However, when the argument that SPC properly implemented

will gain control of processes, reduce rework and the associated costs, reduce delays and their associated costs, and reduce the cost of doing business and the costs for the repairs done for the customers of SA-ALC leading to increased attractiveness to possible privatizing companies, then a new attitude can emerge. It is imperative that training of the meaning of SPC to the privatizing effort be done to all levels of the remanufacturing effort to be sure that low morale does not keep SPC from being implemented.

2.0 Statistical Process Control Evaluation at Kelly

2.1 Methodology of Personnel Contact

The organization of the SA-ALC is divided into Directorates. There are five major Directorates that perform the bulk of the maintenance on base. They are as follows:

Directorate	Name	Function(s) Investigated
LA	Aircraft Directorate	C-5 Maintenance
LD	Aerospace Equipment Directorate	F-15 & F-16 Engine Components Maintenance
LF	Mature Aircraft Directorate	T-38 Maintenance
LP	Propulsion Directorate	Engine Maintenance
TI	Technology & Industrial Directorate	Machine Shop

Each Directorate has a Director and Deputy Director in control of operations. In each case, a point of contact (POC) was identified within each Directorate. The POC was from the engineering function within the Directorate that had, as part of his/her job description, the responsibility of SPC or an interest in the application of SPC in their areas. After contact was made with the POC, a meeting with the Director of each Directorate was solicited and made except with LA. In that case, a telephone conversation was substituted at the request of the Director. In each case, the POC was included when possible. Through these meetings, the TQM principle of involvement from the top down was adhered to and the implicit and explicit cooperation and agreement of the research effort along with any questions that arose from the Director were answered.

2.2 Methodology of Evaluation

From the discussions with the Directors, the POC and his supervision, and shop floor supervision in the maintenance areas, operations were observed as to whether SPC was in use, how it was being used, whether the operations were potential SPC application areas, and whether operations were not suitable to SPC implementation. The project began with an orientation time period and a time set aside to meet with the Directors and the individual directorate POCs. Then, individual directorate investigations were commenced in order to determine the areas

where pilot SPC implementations would be possible. The LD Directorate was chosen for the pilot study for the type of SPC technique involved - attribute charting, the certainty that the SPC effort would highlight the experienced problem areas that precede the final assembly of the components chosen (see the LD Directorate findings for further detail), and the cooperative nature of the management of the directorate as well as the engineering and shop personnel involved. A Gantt chart covering the tasking of the research project is given.

Project Timeline - May 15, 1995 to August 4, 1995													
Category	Task	Project Week, Month											
		1, 5	2, 5	3, 5	4, 6	5, 6	6, 6	7, 6	8, 7	9, 7	10, 7	11, 7	12, 8
Project Orientation	Orientation												
Directorate Meetings	LD, LF, LP, TI, LA Directors		LF, LD		TI	LP LA							
Existing Conditions Observation	LD Area												
	LF Area												
	LP Area												
	LA Area												
	TIM Area												
SPC Project Report	Formulation												
	Finalization												

2.3 Directorate Findings

2.3.1 LD Directorate

The primary repair/refurbish/remanufacture function of this directorate is in the complete disassembly, inspection, repair, reassembly, and test of components of the engines of fighter aircraft. The component parts of these assemblies wear and age fairly consistently, but there is still a high degree of variation in the parts that need to be replaced and/or repaired. After disassembly, the parts of the assemblies are cleaned, inspected, and routed to different areas for repair/refurbish/remanufacture.

SPC was not being utilized in the LD Directorate at the beginning of this project. The task of determining where to begin the SPC effort was significant. The appropriate place to start needed to have a fairly high volume, some degree of problems, and a reasonable chance of cooperation, eventual success, and the promise of shining a spotlight on other problem areas for future SPC application.

The final assembly of the reworked components is done just prior to testing and shipment. The mechanics that complete the assemblies work from kits that are prepared by the parts pool people. The kits are delivered to the building where the final assembly is accomplished. Problems existed, and still do at this point, with the kitting procedure in two targeted assemblies - namely, the Jet Fuel Starter (JFS) and Central Gear Box (CGB) of the F-15. Each mechanic expects that the kit he is about to assemble, which contains about 100 parts and requires a high skill level to assemble, will be complete and all parts be correctly kitted and remanufactured with high quality - of course, final test is the true measure of the quality of the parts and the mechanics can identify problem areas before test and during assembly. If the kit is somehow incomplete, delays occur in the assembly process which can, and often do, translate into aircraft that remain grounded waiting for missing assemblies.

A pilot study was undertaken in each of these two areas. The mechanics obtain a kit from the kit carousel, take the kit to their work station, and begin assembly. This procedure applies to either the JFS or the CGB. As the assembly proceeds, the mechanic often has problems with missing parts in the kit, parts that are in need of further rework, parts that have been mistakenly placed in the wrong kit, too many multiple parts, too few multiple parts, wrong handed parts, etc. The mechanic must handle these problems as they arise. There was no documentation of these problems in the past.

The frequency of problems made these areas good ones for SPC pilot studies. Another reason these were good candidates for the studies was the fact that the problems identified at final assembly would tend to highlight the areas that needed attention in the part preparation areas whether they be procurement, remanufacture, kitting, or some other area. Also, success with these two assemblies and the accompanying SPC procedures could easily be transferred to other assemblies for further investigation and future SPC implementation.

It was determined to generate an inventory sheet to accompany each kit which contained all of the component part numbers, a part description, the quantity that each kit called for, and a space for comments from the mechanic on the status of the parts in the kit during assembly. With 100% coverage of these assemblies, data could be gathered which would allow a Pareto analysis initially to determine the most problematic areas and parts as well as supplying data for the generation of attribute charts on nonconformities in the kitting effort. The study was run through the end of the AFOSR project and was to be continued indefinitely by LD engineers assigned to the area as on-going monitoring of the final assembly areas. In this way, control of the kitting effort can be achieved as well as continuing identification of problem areas with kit components.

Initial results of the Pareto analysis as to cause of kit problems (Charts A and B) and part number per kit problems (Charts C and D) show that part number 366125, decoupler piston, and 367125, generator assembly, were the most frequent part problems with the CGB; part number HRDW080, hardware kit, and part number

367263, duct air inlet, were the most frequent part problems with the JFS; missing parts and getting two parts instead of one were the most frequent problems with the CGB; missing parts and getting two parts instead of one were the most frequent problems with the JFS.

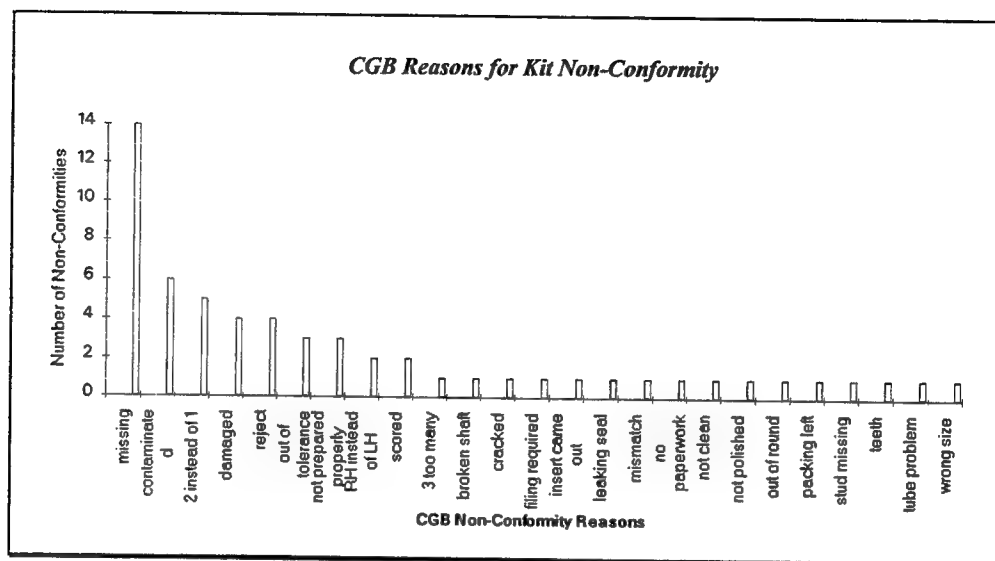


Chart A

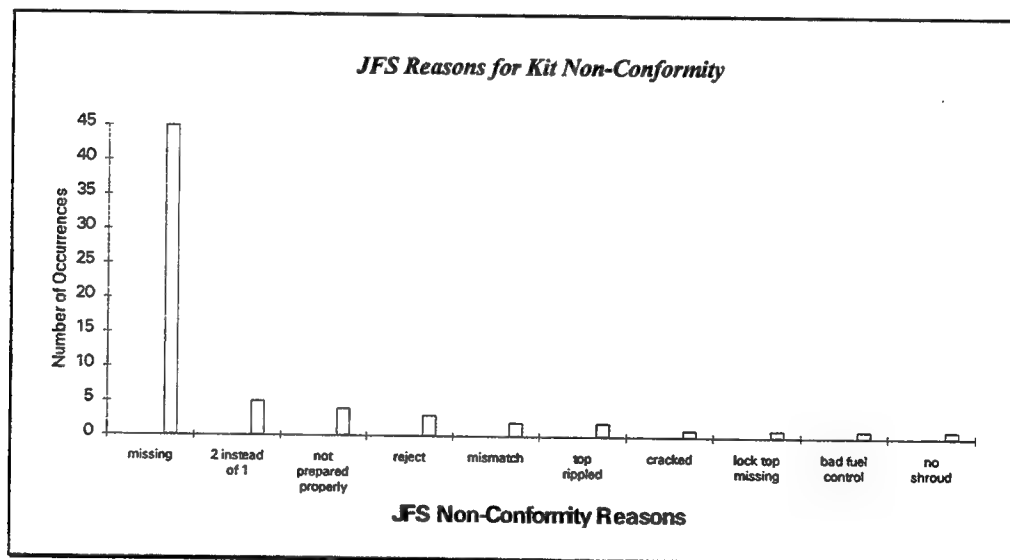


Chart B

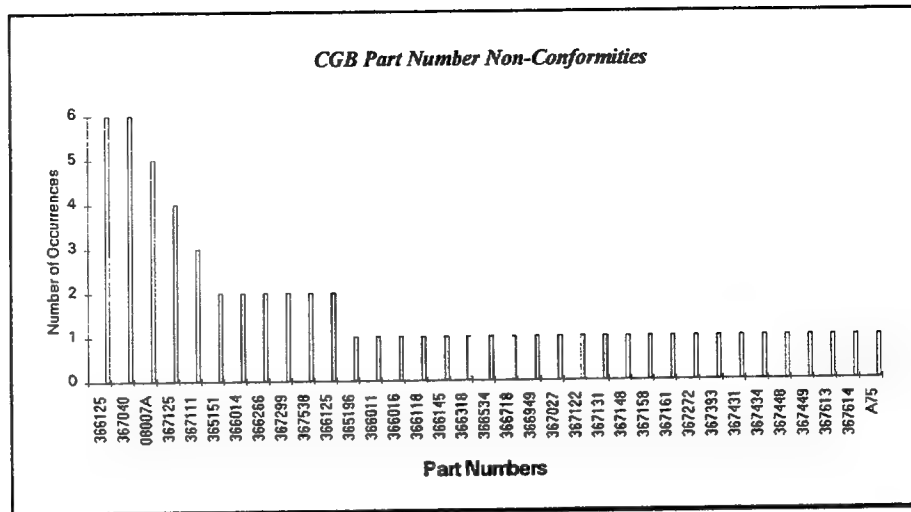


Chart C

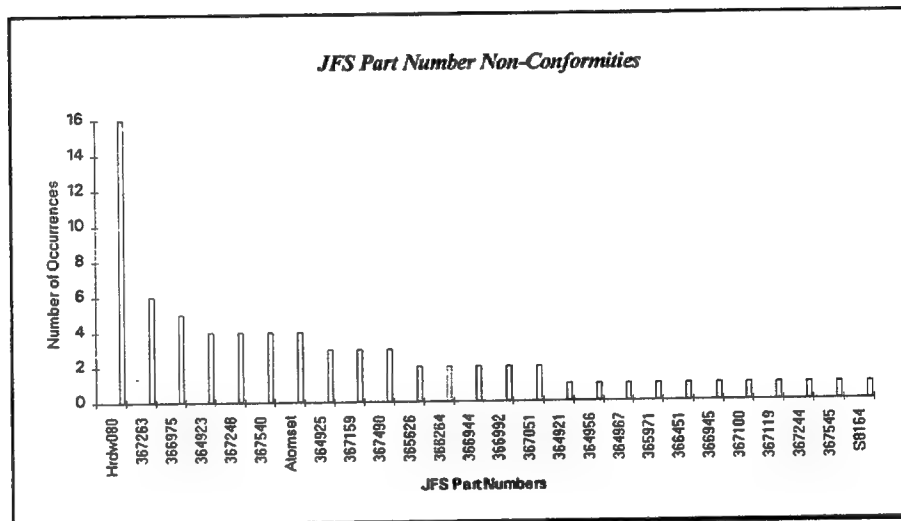


Chart D

Diagnosis of these initial Pareto analyses would suggest further investigation into the areas refurbishing the decoupler piston and generator assemblies for the CGB; further investigation into the hardware kit and duct air inlet for the JFS; and that the kitting procedures and personnel are the largest factor in problems with the kits for both the CGB and the JFS.

Control charting for the CGB and JFS (Charts F and G) show the trial control limits for these assembly operations. Both the CGB and JFS are in control over the time period examined. For the JFS, there are several kits that exhibited between one sigma and two sigma deviations from the mean. The mean, itself, for the JFS shows that the average number of non-conformities per kit is between three and four. In other words, when a kit is

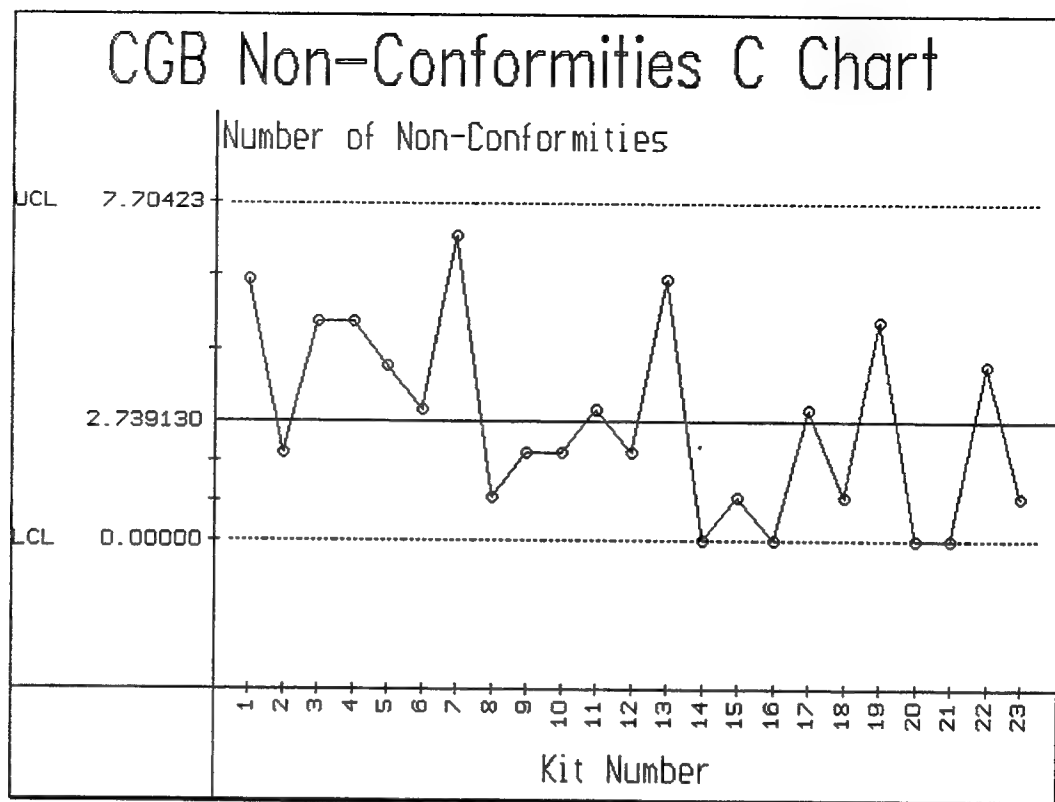


Chart F

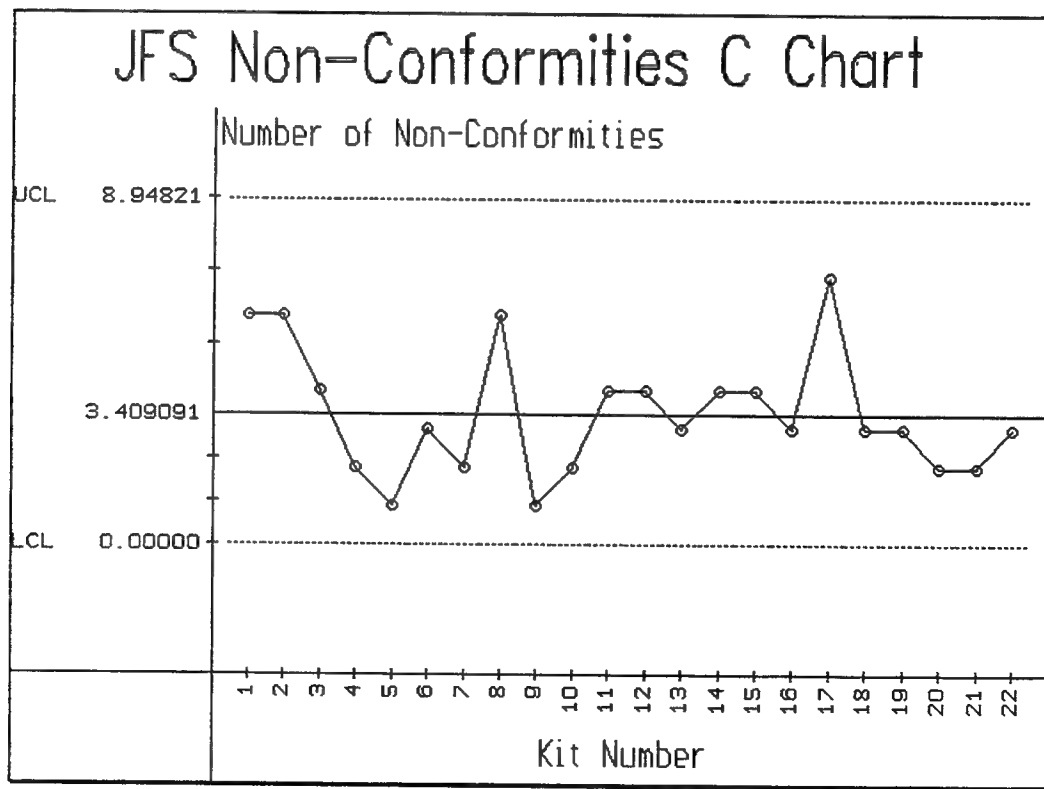


Chart G

retrieved from the kit carousel, there will be either three or four non-conformities causing delays before the assembly process is even begun. For the CGB, there are also several kits that exhibited over one sigma deviation from the mean and one kit that was between two and three deviations from the mean. The CGB mean was almost three meaning that each kit can be expected to have three non-conformities causing delays.

The continuation of this pilot study is recommended for control reasons. The problems that occur before the assembly of the CGB or the JFS are highlighted for further investigation and problem resolution. The same SPC procedures can easily be implemented with the AMAD's (Aircraft Mounted Accessory Drive), for example, and any other assemblies in the LD Directorate. After further problems are highlighted in a backshop, like where the generator assembly is repaired in the CGB, implementation of SPC can be investigated in order to gain control of the backshop and remove that particular part number as a kitting problem.

2.3.2 LF Directorate

The LF Directorate is primarily engaged in the refurbishment of T-38 training aircraft. In the refurbishment, the two longerons that form the upper fuselage structure on each side of the cockpit are replaced. This replacement entails the removal of the two existing longerons by drilling out numerous rivets. The new longerons are then clamped into place, new holes drilled and reamed for riveting. Before the rivets are installed, the operators measure the newly reamed holes and enter the measurements into SPC software for analysis.

This is the only existing example of SPC usage in any of the five directorates as of the Summer, 1995. Unfortunately, the data being gathered and analyzed is not of very much use. The reason for this evaluation is the method of measurement of the holes. SPC variable charting is based upon the inherent variability in repeated measurements. The metrology instrument must be capable of many different measurement values and must be a quality, precision instrument capable of accurate measurements in the hands of a trained operator. The data being gathered does not vary in a significant manner and is suspect. The original SPC procedure was recommended to have a newly purchased metrology instrument, but budgetary constraints caused the present method of measurement to be implemented.

The present procedure of measuring the inside diameter of the holes is through the use of a small hole ball gauge and a micrometer. This metrology method is not of the quality or accuracy to gather the proper form of data to make SPC valuable. The operator must adjust the ball gauge and test-fit it into the hole being measured. Then, the ball gauge is removed from the hole and measured with a micrometer. The compound use of metrology instruments builds in a compounding error. Not only is the fitting of the ball gauge difficult and variable, the second measurement instrument use is unacceptable for accuracy and proper variability concerns. The correct instrument would be a spring-loaded ball probe-type dial gauge with a direct analog or digital readout. These can be purchased for less than \$800.

The application of SPC in this directorate is a good one. However, the measurements upon which the very credibility of SPC depends is not acceptable. The purchase of the proper metrology instrumentation, known by the

LF engineers in charge of the SPC effort, will validate the SPC effort.

There is, perhaps, additional SPC attribute charting potential in the LF Directorate. There is a great deal of electrical wiring disconnection upon arrival of the aircraft for refurbishment. After the work has been done on the longerons, rewiring is accomplished and electrical testing is done. Some SPC charting is possible as to defects in the electrical testing to determine how many failures are occurring requiring rework and accruing additional cost and time expenditures.

2.3.3 LP Directorate

The LP Directorate is responsible for the repair/refurbishment/remanufacture of aircraft jet engine modules and complete engines that SA-ALC produces. There are three major engines, the F-100, the T-56, and the TF-39. The first is a fighter engine, the second is from the C-130, and the third is a C-5 engine. The size difference is remarkable and the procedures for the remanufacture are very different and yet similar. The point is that there are common processes utilized by the directorate on all engines and engine modules. Even though the volume is low, approximately 300 varying kinds of modules per month and 4 engines per month in the case of the F-100, and the variability of the parts that are being repaired on any given machine or process is high due to the engine mix, SPC can still be a good tool to use in controlling the process when the products cannot be.

LP Area	Type of Operation	SPC Application	Comments
High Speed Blade Tip Grinder	Control of overall OD	Variable Charting	Used in the past - could be process-centered SPC application
Plasma Spray Coating Process	HPT Forward Shaft	Variable Charting	Product-centered SPC due to volume
Machining	Any machining operation	Variable Charting	Process-centered SPC on the machine and its capability
Heat Treat	Metal microstructure alteration	Attribute Charting	Go-No Go Evaluation of process using coupons for testing
Plating Shop	<ul style="list-style-type: none"> • Ion concentrations • Inventory tracking system • Defects in plating 	<ul style="list-style-type: none"> • Variable Charting • Attribute Charting • Attribute Charting 	<ul style="list-style-type: none"> • Periodic sampling of plating vats • Non-conformities to schedule • Go-No Go Evaluation using coupons for test
Kitting TF-39	Kitting of parts for assembly of modules	Attribute Charting	Non-conformities to complete kit
Engine Test Cells	Testing of completed unit prior to shipment	Attribute Charting	Number of defects per engine prior to test
Welding	Joining	Attribute Charting	Number of defects as percent of total - x-ray

Although there was no present usage of SPC in the LP Directorate, there has been at least one application of SPC in the past (high speed blade tip grinder) and there are several potential uses of SPC for investigation and pilot testing. The SPC potential applications that have been identified are summarized in the accompanying table. This is not meant to be a comprehensive listing - only a representative example of the great potential of SPC in the LP Directorate. It is important to say again that selective implementation of SPC in areas where application of SPC will be beneficial is preferred over a blanket-type installation of SPC where the application may be in doubt and the motivation is to comply rather than to improve.

There are so many potential areas of SPC application that there is little reason to consider the areas where SPC cannot be utilized. Perhaps the only major areas in the LP Directorate where it would be difficult to apply SPC would be in total engine repair due to the very low volume (four to six per month for the F-100 and the TF-39).

2.3.4 LA Directorate

The LA Directorate primarily repairs/refurbishes the C-5 aircraft. Some of the different tasks that the directorate engages in are completely paint stripping the aircraft, completely re-painting the aircraft, inspection of the entire aircraft as to fatigue cracking, rivet replacement, etc., and repairing the damage found, certain skin panel replacement on the fuselage, the machine shop as a support function, and the bonding shop to repair damage found. There are areas that the application of traditional SPC is possible in this directorate as well as non-traditional applications. There was no present usage of SPC techniques found in the directorate.

In the paint stripping operation, plastic blasting media is used. Over the course of recycled use of the media, the individual particle size of the media deteriorates and must be filtered out and replaced by new media. In order to determine the correct amount of new media to add, the proper procedure is to test the particle size on a regular basis prior to filtration and adding to the media mix. Problems that could and do occur could be with the filtration system filtering out too large a particle, the new media deteriorating at a faster than expected rate, the foreign particles that may find their way into the media, etc. Maintaining a certain level of media is also important in the blasting system. SPC could be implemented in order to track the deterioration rate of the media. In this way, the quality of the media that is being used can be monitored. The regular sampling of the media particle size at various points could be documented and SPC variable X-bar and R charts used to monitor the average particle size, the minimum particle size, the amount of new media added, and the particle size being filtered out of the media mix.

Other possible parameters to track using SPC techniques in the paint stripping hanger would be the blasting nozzle use time, the flow days that the aircraft remains in the hanger, and the man-hours utilized per aircraft in paint stripping.

In the paint hanger, there are several areas that are in need of SPC investigation. The paint thickness at various points on the aircraft can be monitored utilizing eddy current techniques. This data can then be charted to determine if the paint process is in control, if too much or too little paint is being applied, and if the consistency of application of paint is being maintained over the entire aircraft. The paint and primer can be monitored as to pot life

and viscosity to maintain control of the constancy of parameters and to eliminate unwanted variability. The flow days and man-hours per aircraft in the paint hanger can also be monitored.

In the areas of aircraft skin replacement or other areas where many rivets are replaced, SPC can be utilized in order to determine whether holes that are being drilled and reamed are consistent over time. At present, the mechanics that do the repair work on the C-5 do their own inspection of their work. After the entire aircraft is completed, formal inspection occurs. At that time, difficulties may be found that are in need of rework and must be attended to just prior to completion of the aircraft and return to flight status. This causes increased delay in the readiness of the aircraft and increased costs due to rework labor and lost capacity due to delays. SPC could be used by those repeated operations, such as rivet replacement, to gain a greater degree of control and reliability of the work being done much prior to formal inspection thus saving time and rework labor.

In the bonding shop and the machine shop, the kind of work that is being done is of such a unique and variable nature that it would be very difficult to utilize SPC.

2.3.5 TI Directorate

The TI Directorate has the machine shop and the foundry servicing the entire ALC. Although there are many special manufacturing operations in the machine shop of the nature of one-of-a-kind which would not be applicable to the use of SPC, there are operations that are consistently done on several machines that could be combined into a process or machine-oriented SPC analysis. A pilot SPC study on one of these machines can be undertaken, such as the grind-plate-grind processes done on numerous machines working on parts from gas turbine and TF-39 engines, according to the explanation given previously where the different types of parts that are produced by this machine are carefully examined for parameters reflecting critical axis measurements to determine the accuracy of the machine's ability to meet the target measurements. Then, regardless of the part that is being run on the machine, the deviation from the particular targets chosen for that particular part can be charted giving indication of the machine's continued capability of generating quality output. One of the engineers in the machine shop has been briefed about this approach.

The foundry is a specialized manufacturer of castings that are subject to non-destructive x-ray inspection. The volume is fairly low and the variety of parts is relatively high indicating one potential SPC technique. An attribute chart on the number of defects produced per pour would be meaningful to the operation of the foundry. With this approach, the variability of the kinds of parts would not be important. The actual process of casting the parts, or pouring the molten metal, becomes the focal point. The real problem might be in the design of the mold or in the mix of the sand (too much moisture in a green sand mold causing bubbles, for example), but the problem would show up as defects in the x-ray analysis. Then further investigation would reveal the initial problem. An average number of defects per pour would give a measure of the excellent work that is produced by the foundry.

3.0 Conclusions and Recommendations

A repair facility responsible for the sophisticated and high technology products that SA-ALC is responsible for should be using statistical process control heavily. Realizing that the traditional application of SPC is rare in the depot, there are numerous applications for its use in all five of the directorates investigated. It is recommended that these identified applications be implemented as soon as possible and in the recommended priority. The level of expertise needed to make SPC usable and successful at Kelly is at least at the industrial engineering Master's degree level. Traditional exposure to SPC techniques really only covers the common applications of the discipline and Kelly is certainly not common.

Knowledge of the proper priority approach to implementation of SPC is also imperative to insure success. First, meaningful metrics must be gathered whenever possible. The type of metrics, such as Pareto diagrams and run charts, should be easy to develop from the data gathered. Training into the type of data to be gathered, the type of metric method to use, and the evaluation of the result must be done prior to beginning the effort. Second, attempts should be made to find SPC attribute charting applications. Since the statistics involved in attribute charting is much easier to explain than the statistics of variable charting, this is a much more logical place to start with novice SPC users. Acceptance of the concepts will come more quickly if the people involved understand as they go along. Lastly, SPC variable charting technique application should be implemented where possible. Special training for all involved should be undertaken to be sure of the veracity of the data gathered, the accuracy of the charting done, and the proper and meaningful interpretation and evaluation of the results on an on-going basis. Remember, SPC is a dynamic, real-time tool. To be utilized to its fullest potential, it must be maintained regularly and updated often. This can be accomplished by existing engineers after proper training.

Continued support of SA-ALC statistical process control implementation effort by experts in the field is recommended. Utilizing outside assistance, such as this summer's AFOSR project and the possibility of add-on extensions to the summer project, will insure that the SPC effort is accomplished in other directorates, and will relieve the added task pressure on existing SA-ALC engineers. Also, a slow but deliberate approach is recommended for clarity, accuracy, and meaningful information to be the result. The SPC effort should not be entered into by untrained individuals. A hastily begun effort is not worth the effort.

The techniques involved in the implementation of SPC are just as important as the SPC analysis itself. If the SPC effort is to succeed, and it can, then the implementation and continued use of SPC must be done carefully and with expert consultation. The presence of working and usable SPC installations will be a definite plus in the privatization effort at Kelly. This is another reason that the importance of the understanding and training in SPC by everyone involved in an application is so very crucial. Time and task constraints on existing personnel at SA-ALC make the continued SPC training and implementation effort best done with the assistance of outside expertise. Relying on Kelly engineers exclusively for the SPC effort can mean insufficient knowledge, insufficient preparation, unwise application of the techniques, and loss of confidence in an otherwise very useful tool.

Reduction of rework, improvement in quality, reduction of time delays, improvement in product flow, increased efficiency of communication, and increased potential of privatization are all benefits of the immediate implementation and continued use of SPC at SA-ALC, Kelly Air Force Base, San Antonio, Texas.

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DEVELOPMENT OF A COST-EFFECTIVE ORGANIZATIONAL SUPPORT SYSTEM
BASED ON THE WORLD WIDE WEB: A CASE STUDY

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Abstract

Two new events central to re-engineering the data flows in organizations have instigated new research directions in organizational support systems: the first is the advent of PC databases with their relatively easy to use interface. This has lowered the cost of developing and maintaining electronic databases, which is leading to the creation of a large number of distributed electronic databases, collected and maintained by individual sections of the organization, but with information needed throughout the organization. The second event is the advent of the Internet and the World-Wide Web, which provides a new and very cost-effective channel for disseminating this information, if one considers marginal costs, rather than total costs. Marginal costing is more appropriate for decision making.

This case study examines how a small organization in the Air Force, responsible for collecting, maintaining, and disseminating information about automatic test systems (ATS) to the entire Air Force used the World Wide Web to re-engineer their customer support function. The Web replaces a process of mailing several floppy disks to more than 500 end-users several times a year. This savings is achieved at almost no marginal cost for the Air Force.

The research followed a "bottoms-up" approach, looking at some of the new tools available on the World Wide Web, and how they might most effectively be used in an organizational support system. In addition to the data distributed by mailing out floppy disks to users, the lower cost of providing information via the Web allowed the section to make additional databases and knowledgebases available to the entire organization.

As a result of this research, the organization will begin the development of a system to disseminate its data and receive customer feedback via the World Wide Web.

Development of a Cost-Effective Organizational Support System based on the World Wide Web: A Case Study¹

by

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Introduction

The sudden advent of the World-Wide-Web (WWW) in late 1993 provides an opportunity for the development of organizational support systems. The use of the Web for Interorganizational systems (basically, marketing) has already been explored in depth [Hoffman, D.L. and T.P. Novak (1995)] To date, however, its use in organizational support systems has received much less attention, although some thought to intraorganizational applications has been made [Chandler, David M (1995)] .

The basis of the current Web protocol was first suggested at CERN in 1989 as a distributed hypermedia system². The system is a client/server system, and the earliest clients and servers were text-based tools which, while interesting to information technology professionals, were not really suitable for use by general decision makers. It was not until the development and widespread dissemination of the NCSA graphical WWW clients and servers in 1993 that this technology became widely accessible. Essentially, the WWW is a point-and-click interface running via Transmission Control Protocol/Internet Protocol (TCP/IP) over the Internet; however, knowledge of such technical details as TCP/IP are not needed by users of the technology. To the user, the WWW looks like a local, icon-based system; although it may well be retrieving data from international locations over the Internet.

Growth of the WWW appears to have followed a normal S-diffusion curve, as shown in Figure 1; however, since this is a log plot, the linear segment from mid-1993 until late 1994 is actually exponential growth, while the section from late 1992 until mid-1993 is roughly e^{e^x} (based on a very rudimentary "eyeball" analysis). In addition, this metering was only done over a technology which was being phased out, i.e., during the first quarter of 1995, the NSFNET Backbone Service (where these data were collected) was successfully transitioned to a new architecture, where traffic is exchanged at interconnection points called Network Access Points (NAPs.) The

¹ This research was sponsored by the Air Force Office of Scientific Research, Bolling Air Force Base, DC.

² World-Wide Web FAQ, URL: http://sunsite.unc.edu/boutell/faq/www_faq.html

estimate of actual total traffic is shown in Figure 2. Note that the projection falls short of the actual traffic for January-April, 1995.

While the new technology makes it very easy for any member of the organization to access information, the CERN HTTP protocol provides

an application-level protocol with the lightness and speed necessary for distributed, collaborative, hyper media information systems. It is a generic, stateless, object-oriented protocol which can be used for many tasks, such as name servers and distributed object management systems, through extension of its request methods (commands). A feature of HTTP is the typing and negotiation of data representation, allowing systems to be built independently of the data being transferred. [Berners-Lee, Tim, "Overview of the HTTP Protocol," <http://WWW.W3.ORG/hypertext/WWW/Protocols/Overview.html>]

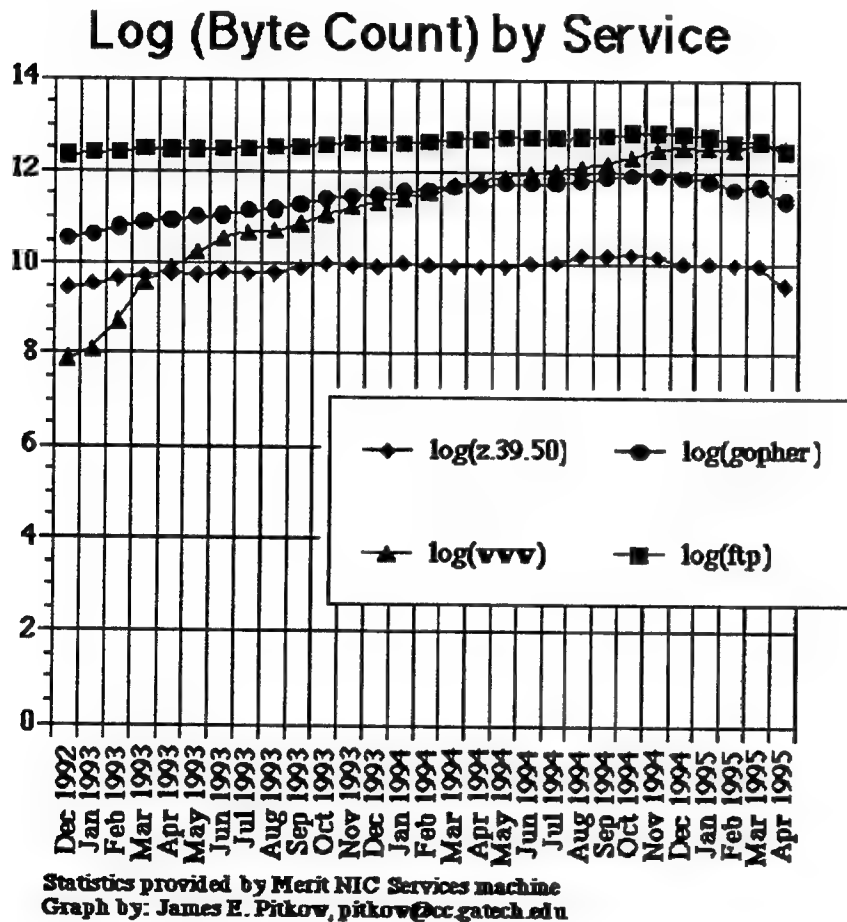


Figure 1. Measured used of WWW

Third Degree Polynomial Curve Fitting for Bytes Transferred Per Month By Service

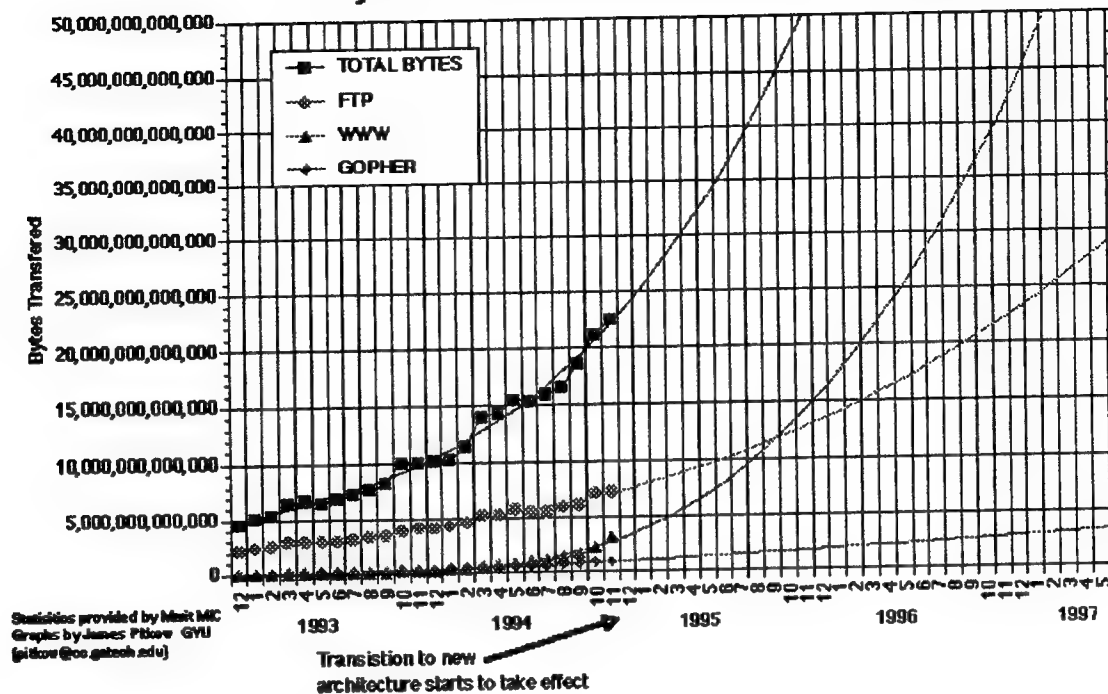


Figure 2. Extrapolated use of WWW

In short, the protocol provides an efficient way of publishing information that can be received independently of the recipients' platforms, making it a potential candidate as the underlying protocol for an Organizational Support System (OSS). The HTTP protocol is the closest implementation to date of Bush's vision [Bush, V, "As We May Think]. Early hypertext/hypermedia systems allowed authors to readily link resources within the system: e.g., Hypercard³, while it allowed the author to reference any document on the host Macintosh, only allowed facile access to Hypercard "cards;" accessing documents which were not Hypercard documents, or other applications, or resources on another computer was quite difficult. A Web server, on the other hand, is an independent application which serves resources from anywhere on the Internet to anywhere on the Internet, allowing authors to reference documents (easily) as well as models, data, and knowledgebases, as shown in Figure 3. Furthermore, the models, knowledgebases, and data need not reside at the same physical location. Ignoring those servers restricted by access controls, every server has read-only access to all the resources—data, models, knowledgebases, etc. — on every other server, as well as write access to selected servers.

³ Not to pick on Hypercard: this was true of all the early hypermedia systems. See, e.g. [Berners-Lee, Tim, "Press FAQ," <http://www.w3.org/hypertext/WWW/People/Berners-Lee/FAQ.html>]

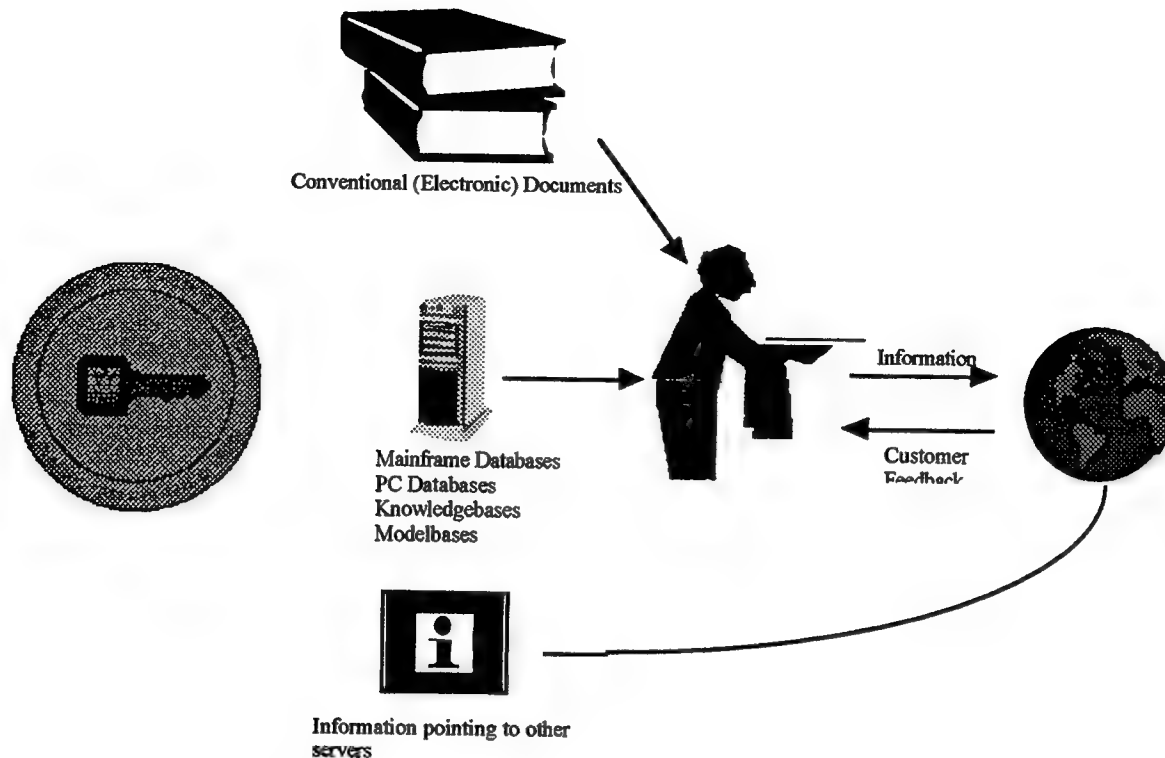
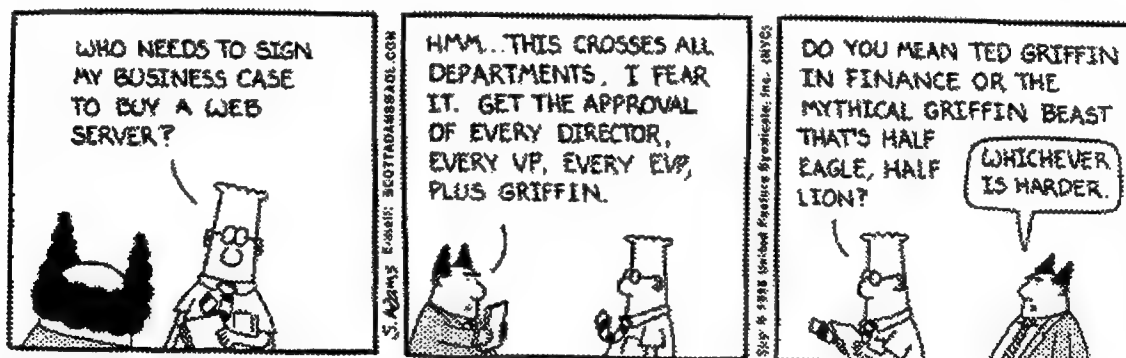


Figure 3. Web Server Capabilities as an OSS

There are two major considerations for using the Web: technical and organizational. The technical requirements are changing rapidly in the direction of increasing ease of access as better, more usable tools become available. Organizational considerations, however, are another matter, as depicted by Scott Adams in Figure 4.



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Figure 4. Organizational Considerations for Using the Web. Dilbert reprinted by permission, United Features Syndicate, Inc.

Organizations have responded to the Web with a spectrum of approaches, from the University of Texas, where the policy is that

Web publishers at UT Austin are responsible for the content of the pages they publish and are expected to abide by the highest standards of quality and responsibility. These responsibilities apply to all publishers, whether colleges, departments, student organizations, or individuals. Publishers are also required to comply with all UT System rules, University policies, and state and federal laws concerning appropriate use of computers.

[Team Web, "Publishing Guidelines," The University of Texas at Austin, 4 June 1995, <http://www.utexas.edu/teamweb/guidelines/>]. The key point is that all members of the organization who wish to publish are responsible for their own Web pages, with no prior review.

At the opposite end of the spectrum is the policy at another university where all Web pages must receive prior approval, both from the author's Dean and from the vice-president of Computing, before being allowed on the Web (so far, no documents whatsoever have made it through the review process, except for a few pages originating in the vice-president's office).

Most organizations will have a policy that lies between the Scylla of making individual members of the organization fully responsible for their pages with no prior review (with the concomitant risks of individual irresponsibility adversely affecting the organization), and the Charybdis of making the CIO responsible for all pages (with the result that the limitations on the CIO's time keep most pages off the Web, and the organization loses the not inconsiderable benefits available from the Web).

In addition to the organizational concerns about dissemination of information to, potentially, more than 20,000,000 persons, authors must also consider the potential recipients of the information. This information can reach all members of a large organization, members with different cognitive styles, hardware, software, and connectivity.

The project described here was the initial investigation of an OSS for an Air Force section. The research was "bottoms-up" i.e., the researchers investigated a variety of Web tools for applicability to an OSS for the organization. Section 2 of this document will describe some of the background of that organization and the potential for cost savings by installing a Web-based OSS; section 3 will discuss, in a very general way, technical consideration and marginal costs for any organization using the Web for an OSS; section 4 will discuss the specifics of the "bottoms-up" research: an estimate of the effort involved for each extension of a Website beyond the basics (along with a brief "how-to" guide); and section 5 will review Air Force policy on the Web. The final section consists of our conclusions and recommendations.

Organizational Background

The LDA Automatic Test Systems (ATS) Product Group Manager (PGM) in conjunction with the ATS PGM Business Office has the mission of providing and implementing ATS policy for all Air Force weapon system acquisitions and sustainment activities. The Advanced Diagnostic Technology Insertion Center (ADTIC) provides engineering and research support to the ATS PGM on ATS standardization and technology insertion

issues. Examples of current projects involving ATS standardization include ABBET (A Broad Based Environment for Test), VTest (Virtual Test), VXI Plug and Play Consortium, and development of Open System Architectures. Technology insertion projects currently under development and verification include artificial intelligence, neural networks, and imaging techniques including both X-ray and thermal. Information about this work is needed throughout the Air Force. In terms of intraorganization sharing theory, this information is already provided to the organization by the information subsidies approach [Anitesh Barua, Suryanarayanan Ravindran, Andrew B. Whinston, "Organizational Mechanisms for Facilitating Information Sharing Between Cross-Functional Teams," <http://cism.bus.utexas.edu/suri/in.html>, 1995.]—i.e., a section was given, as part of its mission and for which it is compensated, to distribute all this information to the entire organization. Note that the new technology which reduces this cost of providing information reduces the level of subsidy necessary, so that more such information can now be provided by this mechanism.

The ADTIC does extensive database and information systems work to satisfy technical support requirements in the AF acquisition and ATS technical communities. A small example of the information customarily provided includes ATS technical system specifications, AF ATS inventory items, and Unit Under Test (UUT) information. An Automatic Test System Selection Process (ATSSP) is currently under development and is a candidate for complete automation. This process and its sub-processes are in response to new draft DoD ATS policy 5000.xxx.

Currently, some of this information is mailed to customers on floppy disks. A total of several hundred floppies are used to send the data. This is both slow and expensive. In addition, potential customers may not realize the information is available, and may therefore not avail themselves of it, with a resultant cost in terms of sub-optimal decisions being made because all information in the organization is not being effectively utilized. The cost savings from this new OSS will be:

1. The reduction of staff-effort to support existing paper intensive type tasks;
2. The reduction of staff-effort and postage required for the floppy-based approach.
3. Improved decision making from greater availability of relevant information.

The information systems developed will provide a significant productivity increases within both the ADTIC and ATS PGM offices. In addition to the productivity increase, the ATS acquisition and user communities will also have the support and data to make informed ATS decisions which will yield significant cost savings. The AF will also benefit from the experience and training which will occur during the development phase of each tool. In summary, the information systems will not only provide significant benefits to the ATS PGM and the ADTIC but in whole benefit the Air Force Materiel Command (AFMC).

Overall Technical Requirements and Marginal Cost of Implementing a Web Site

The technical requirements are

- Hardware

- Software
- Connectivity.

The only hardware required, either to publish or receive information from the Web is a Windows-capable PC (i.e., 486 or better), Mac (68030 or better), or UNIX workstation; for most organizations, most decision-makers will have access to such a platform. In addition, VMS and VM clients and servers are available, for organizations using a centralized computing model.

Software for all three platforms is available at no cost, although the free software provides only limited technical support, and, as of today, does not implement transparent encryption for sensitive data. If technical support and encryption are necessary, the publishing software for the information providers is around \$5,000, while the client software for information receivers is less than \$100. The marginal cost, then, for a large organization would be roughly \$100 per employee, if the organization is unable to avail itself of the freeware versions.

The final item is connectivity. If employees already have Internet email connections between all geographically dispersed offices, they have adequate connectivity to receive Web documents. This is the most difficult and variable factor in implementing the Web as an organizational support system. It really makes little sense to use the Web if all information is to be exchanged over a local-area-network (LAN)-users can more easily access documents from a shared drive. The power of the Web is that it provides a very easy way to disseminate digital information across the Internet to a large base of non-technical recipients. Connectivity in the U.S. is currently available at less than \$10/hour, for a single employee at a remote site in a rural area. In all major cities, there are now Internet providers with local Points of Presence (POPs). For the cost of a local phone call, Internet access is available at low speeds for around \$25 per month, or at high speed for around \$100 per month. For an organization like the Air Force which intends to provide all employees high-speed access to the Internet for email purposes, the marginal cost of Web connectivity could be \$0; however, organizations which are not connected may find the cost as high as \$100 per month per location for Internet access. In addition, if sites have no connectivity at all, LANs must be installed to provide employees access to the Internet gateway.

For the specific case, all information receivers had access to a PC, though some had Macintosh systems, some Windows (both 16 and 32 bit versions) systems, and others UNIX platforms; the receivers also all had, or were to obtain in the near future, high-speed access to the Internet. The information provider, ADTIC, intends to provide freeware client software, tailored to the application. Thus, the marginal cost for this application was near \$0 per employee.

Specific Web-based applications and features developed for the LDAE division

The summer research encompassed four separate projects: image maps, development of a customer feedback system, development of a gateway to provide access to an existing FoxPro ATS database, and development of a publishing system for electronic division documents that need to be distributed to customers dispersed throughout the Air Force.

Imagemaps

Imagemaps, discussed above, should be used sparingly; however, to provide the LDAE division with the capability to include imagemaps in their Web pages, a prototype (based on Figure 3) can be duplicated and modified. The summer research developed documentation and software which allows LDAE to develop additional imagemaps, should they so desire.

Customer feedback system

This system consists of a commercial program used for anonymous feedback, and a Perl script which allows attributed feedback and requests. If the customer requests action, the date and time are automatically recorded, and the response may be entered. When the request receives attention, this date and time may be added to the file, so that management may track the number of requests and mean response times. In addition, this allows a much higher level of service with fewer personnel. With conventional approaches, many customers may be unaware of the contact for a specific program; if the customers are at a geographically remote location, time differences may make telephone communications very inconvenient for both the customer and the support organization.

Conversely, the current system places requests before all members working on a given program, so that the person with primary responsibility (OPR) is assured of seeing the request and taking some action. Again, one important feature, for management, is that the date and time of every request and response is logged by the system.

As implemented, customers can provide anonymous feedback for candid statements. This feedback may only be seen by the organization to which it is directed. In addition, customers may provide attributed feedback with requests, comments, etc., which may be seen by all other customers of the organization. Thus, using this facility, customers may be able to solve each others problems, and may also see the solutions to problems faced by other customers, so that the same information need not be re-iterated to all customers individually.

These responses are organized by functional area, again, with anonymous and attributed feedback facilities for each area.

Access to Automated Test Systems Databases

Most of the summer research area was the development of a gateway to a FoxPro database. This was, technically, the most difficult and involved effort, although it represents only a small portion of the information currently available on the Website. Development of this new type of gateway involved extensive basic research to produce the working prototype which currently allows full access to most of the database. Additional query capability, as well as an automated procedure for accessing future databases remains to be developed; however, the application is well documented, so Air Force personnel will be able to maintain it with minimal assistance.

Development of a publishing system

Much of the impetus for a Website is to distribute, more economically, all the information gathered by the ATS group for the benefit of users throughout the Air Force. This information includes meeting minutes, pol-

icy statements, and technical information. As discussed above, this is a fairly simple procedure, requiring minimal technical skills on the part of the publisher. Of the possible approaches, the one adopted is to use the ATS division's standard word processor. Part of the summer effort included no-cost upgrades of the division's existing word processor to enable it to save division documents in the Web publishing language, Hypertext Markup Language (HTML).

Division personnel learned how to use this feature, and converted several documents with limited assistance. At the end of the summer program, a number of these personnel were trained to convert documents and install them on the Website without any assistance. This has enabled the division to publish a large quantity of its material already, and thereby distribute this material at almost no marginal cost.

Organizational Considerations

Security Issues

There are two different security concerns with a Web server. Most of this applies directly to the UNIX servers, where problems are well documented, but, since the security problems are somewhat generic, the concerns apply to other platforms as well.

The Web server provides, *prima facie*, excellent security. While the server requires resources that cause it to be run from the root account on UNIX, persons accessing the server are given the privileges accorded to an anonymous login account. A documentroot is declared, and readers are not allowed any access to resources outside the tree headed by documentroot. In addition, access may be restricted to specific IP addresses, and passwords may be enforced as well.

The first problem is that, at least on UNIX platforms, that security lapses have been discovered [DDN Security Coordination Center, "Defense Data Network Security Bulletin," Security Bulletin 9506, http://www.af.mil/mil-only/DDN_sec_9506.html, 1995.]. Basically, long strings are sent to the server, and, if a poorly written input routine is accessed, the string may be allowed to overwrite the operating system. Skilled and malicious hackers can ensure that the string overwriting the operating system consists of destructive binary commands, giving the equivalent of a remote login to the system as root. This could give the hackers access to all resources on the system. There are at least two responses: on a Windows NT based system, the server can run as an unprivileged user, rather than as a system administrator. Thus, even if hackers succeed in bypassing all the server security, the NT security will prevent any further damage. A second alternative is to run the server on a machine with no other resources, so that an attack will only crash the server.

The second security issue occurs when the server is used to send information only to trusted IP addresses or users with passwords, information which is not to leave the organization. Hackers with packet sniffers or domain name spoofers can potentially bypass the server security and access the data. For this reason, extremely sensitive data should only be served by secure servers which encrypt and decrypt the data. Such servers now exist for Windows, UNIX, and Macintosh platforms. An alternative is to eschew the Web server for all sensitive data.

Air Force Policy

The official Air Force Policy, as of June 1995, is detailed in two documents: "DoD policy on electronic information publishing," by John M. Deutch, 17 Feb. 1995, [<http://www.af.mil/mil-only/policy-DOD.html>]; "HQ AFMC Interim Internet Policy," by Olin A. Howard, 3 February 1995 [<http://oasun1.wpafb.af.mil:12000/organizations/HQ-AFMC/SC/policy.html>]. Basically, these policies apply to information published and available to all users on the Internet: they do not address servers restricted to the organization (e.g., the Air Force). If the information is on the Web with no restriction, the server

1. must be approved by a Designated Approval Authority (DAA);
2. must prominently display the caveat:

Official U. S. government system for authorized use only. Do not discuss, enter, transfer, process, or transmit classified/sensitive national security information of greater sensitivity than that for which this system is authorized. Use of this system constitutes consent to security testing and monitoring. Unauthorized use could result in criminal prosecution.

3. must have all materials on the server cleared for public release.

For this reason, the Web site constructed for the Air Force is on a separate system with no resources that would cause serious inconvenience if a hacker managed to crash the system, and is restricted to .mil and .gov named sites, pending approval of the DAA.

This is a good interim solution, but, for longer term, the server needs to allow more general access, since some members of the organization, not directly connected to the Internet via a military connection, will need to access the system from a site provided by a commercial Internet provider. Thus, in order to allow access by such venues, the server will be submitted to the DAA for approval of unrestricted access.

Conclusions and Recommendations

This case study was done using a "bottoms-up" approach, in which various features of the World Wide Web were explored for possible uses in an organizational support system. With a modicum of effort, the researchers developed a prototype Web Site which showed

1. The efficacy and cost savings possible by replacing a system of mailing floppy disks to remote users with a Web gateway to a PC database;
2. The ability to provide users with a mechanism for anonymous feedback to the ADTIC section;
3. The ability to provide users with a suite of forums for discussing various topics related to the ADTIC mission, such as standards for test equipment.
4. An easy way for all ADTIC policies and results to be published.

The overall architecture of the prototype is shown in Figure 5.

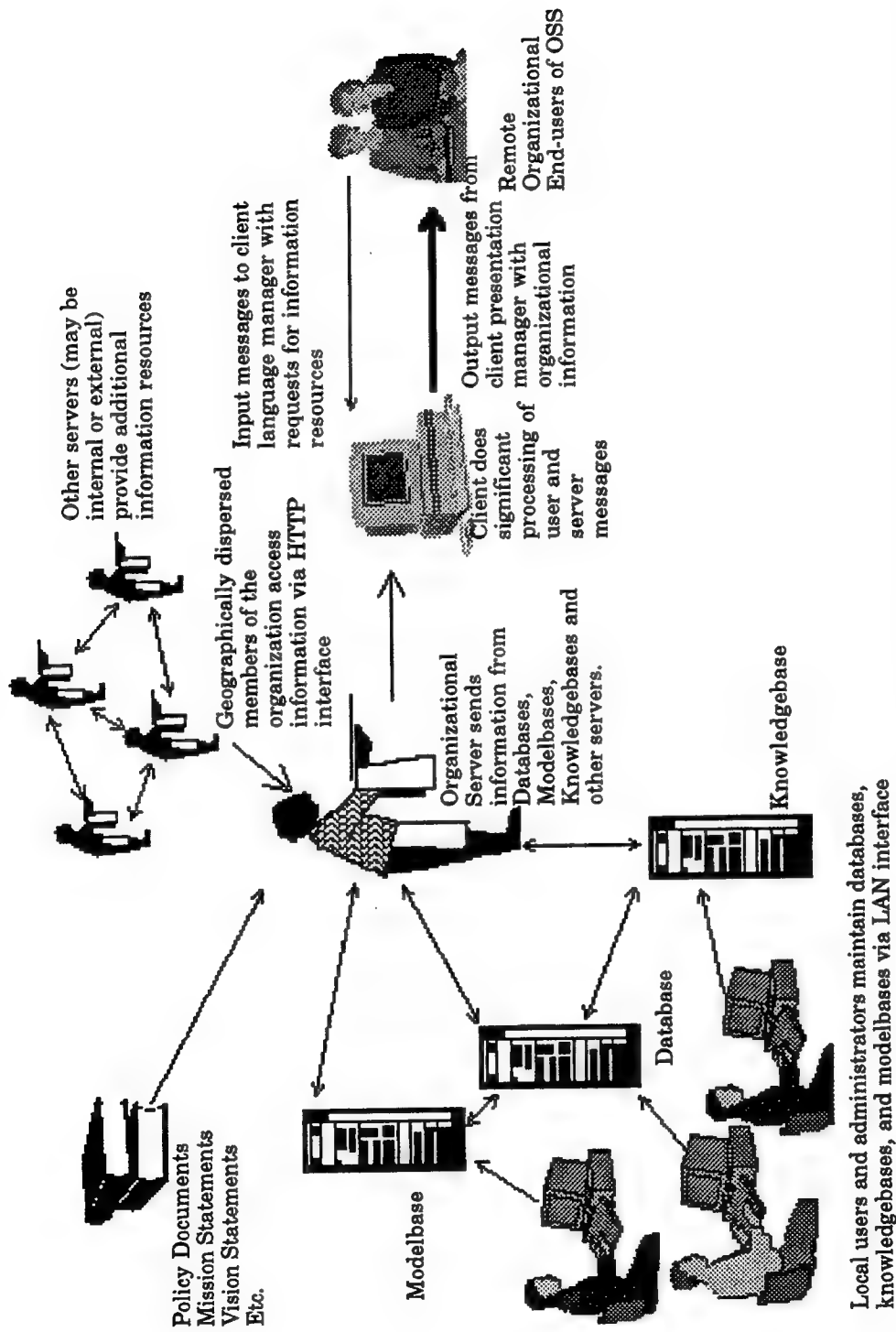


Figure 5. Organizational Architecture of OSS to deliver PC database, modelbase, and knowledgebase information to remote members of the organization.

The prototype was done on an existing 486 based system which was used for other purposes during the prototyping stage, the final server will require a dedicated machine. Performance problems and potential security problems observed with the 486 indicate that a dedicated high-performance Pentium will be required for the production server.

Marginal costs for providing this information to intra-organizational customers throughout the U.S. Department of Defense are near \$0 for recipients, and less costly to the information providers than the prior system, while delivering more data in a more timely manner.

Thus, we recommend that the ADTIC move ahead with full implementation of the Web Site, and extend the current work to additional ATS databases.

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**Determining Statistical Validity of Sample size and Frequency
in Analyzing Toxic Air contaminants in a Production Environment**

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**DETERMINING STATISTICAL VALIDITY OF SAMPLE SIZE AND FREQUENCY
IN ANALYZING TOXIC AIR CONTAMINANTS IN A PRODUCTION ENVIRONMENT**

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Abstract

The accidental emission or release of various kinds of toxic or hazardous air pollutants into the atmosphere over the years has resulted in serious health consequences and even death. These have included particulate matter from volatile and semi-volatile organic compounds and others, both known and unknown. It has become a distinct necessity to control and even eliminate the hazardous effects of these and other sources of pollution. There must be a solid, well-planned, scientific approach to the modeling and validation testing of emissions reduction systems both nationally and worldwide. In particular, the metal casting industry has committed itself to a resolution of this problem by effective and prompt treatment and disposal of process residues, while containing or reducing costs. Such an effort necessarily requires extensive sampling and testing of the ambient atmosphere. The purpose of this research effort is to contribute to the theoretical foundation for a sampling plan which validates the selected sample size, test frequency, and methodology to ensure that samples of the lowest volume of the total air emission field provide data which are statistically sound or valid.

DETERMINING STATISTICAL VALIDITY OF SAMPLE SIZE AND FREQUENCY IN ANALYZING TOXIC AIR CONTAMINANTS IN A PRODUCTION ENVIRONMENT

James Ervin Glover, Ph.D.

Introduction and Historical Perspective

Quality control involves sampling procedures in which important features or characteristics of a product are observed, measured, assessed, and compared carefully with some type of standard. As it has become increasingly clear that an effective quality control program enhances the quality of products being produced and, hence, increases profits, it is no small wonder that it is of major importance in an industrial production setting. It was during the 1920's that statistical sampling and analysis were first used with some success in a production setting in the United States. One major application of this concept was that of locating or isolating abnormalities or difficulties during the production process, along with the systematic reduction of variability. And, although Walter A. Shewhart, a statistician at Bell Telephone Laboratories, developed the concept of a statistical control chart in 1924, it was not until the advent of World War II that the use of control charts became popular, primarily because of the necessity of maintaining quality in production processes during that period. And, with the emergence of the space program in the United States, statistical quality control and the generalized area of quality assurance exhibited phenomenal development in the 1950's and 1960's. Moreover, it is a well-known fact that quality control was an important factor in the development of Japan's industrial economy, thanks to the work of W. Edwards Deming, who served as a consultant to Japan for a period after World War II.

Methodology

The method of control charts has many benefits which this research effort utilizes in determining if randomly collected air pollution data adheres to an acceptable level of quality. The method, in turn, can be generalized to determine whether or not the performance of a generic production process is maintaining a standard level of quality.

As any production process will experience some variability, due essentially to chance or uncontrollable or random sources of variation, such a process is said to be "in-statistical-control". On the other hand, if the process

experiences a more serious type of non-random variability in key performance measures, arising from something like one of a number of operator errors, such as an improperly adjusted dial on a machine or an inadvertent recording, then the process is said to be "out-of-statistical-control".

Although a successful production process may actually operate in-control for an extended period of time, wherein the process is producing a high-quality or acceptable product, it is important to note that a gradual or sudden "shift" may occur which requires immediate detection. Obviously, if detection is null or slow, many defective items are produced, resulting in needless waste and a considerable increase in cost of production.

This is precisely why a control chart is so important. It is designed to detect and isolate the "out-of-control" or non-random behavior of a production process. This is done by sampling or measuring some desired quality characteristic, over time, and determining an average value (centerline), an upper control limit, and a lower control limit.

Nature of Control Limits

In addition to using control charts to maintain proper surveillance of a production process, the routine systematic measurement of data frequently allows management to assess process feasibility and capability. The continual sampling and estimation of the mean and standard deviation of the selected performance characteristic often sheds new light on what the process can achieve in terms of random variation and mean performance, even if the process remains in-control for extended periods of time. It is important to note that the control limits are designed to control the probability of making, on one hand, the error of concluding that a production process is out of control when, in fact, it is not and, on the other hand, the error of not finding the process out of control when, in fact, it is. It is in this sense that the fundamental idea of the control chart is similar to that of hypothesis testing. The control chart is of critical importance in that its structure can often prevent an over-reaction to changes that represent only random fluctuations,, which can, in turn, lead to modifications in the production process, which may create problems that are difficult to solve.

Choice and Reduction of Sample Size

A fundamental concern of this effort is to determine a methodology for reducing sample size in any given experiment (e.g. Determining Emissions of Toxic Air Contaminants) while maintaining the validity of the data.

The major components determining the design of the control chart include sample size taken in each sample subgroup, the frequency of sampling, and the width of the control limits. These components are driven, in large measure, by practical and economic considerations, particularly if the process continues to be out-of-control for an extended period of time. The cost associated with investigation and subsequent search for assignable causes directly impacts both sampling frequency and the width of an acceptable region (i.e., control limits). A high sampling frequency with relatively small sample size is the proper strategy if the cost of producing nonconforming items is great. Although a sample size $n = 4, 5, 6$ or 7 is considered to be generally small in statistical measurements for inference purposes, such a sample size is considered valid for quality control purposes, and it is generally considered to be more effective to sample frequently with a small sample size, according to Walpole and Myers [4]. The virtual sample size is many times larger than that used in a sample subgroup, since the process of quality control is a continuing one, and the results produced by one sample or set of samples will, in turn, be followed by results from many more.

The \bar{X} -Chart and Control Limits

Central tendency for collected data is controlled by the \bar{X} Chart, where means of relatively small samples are plotted on the control chart. Variability around the mean is indicated by the standard deviation, or the range in the sample, when dealing with continuous data (variable measures). On the other hand, when dealing with attribute data (characteristics which reflect whether or not the individual product conforms: (defective or not)), the proportion of defectives from a sample is often the quantity plotted on the chart.

A random variable is a function which assigns a real number to each element in the sample space. The control limits for the \bar{X} Chart are based specifically on the standard deviation of the random variable \bar{X} , where \bar{X} is the mean of the sample measurements. If μ and σ are the finite mean and standard deviation, respectively, of the universal or parent distribution, then the mean and standard deviation of the distribution of the sample mean are known to be $\mu_{\bar{X}}$ and $\sigma_{\bar{X}}$, given by :

$$\mu_{\bar{X}} = \mu \quad (1)$$

$$\text{and } \sigma_{\bar{X}} = \frac{\sigma}{\sqrt{n}}, \quad (2)$$

$$\text{where } \bar{X} = \frac{\sum_{i=1}^n X_i}{n} \quad (3)$$

and X_1, X_2, \dots, X_n represent a random sample of size n .

One can deduce from (2) that the variation in the sample mean, \bar{X} , from one random sample to the next, depends upon two factors: the variation from unit to unit to unit in the parent population (as measured by σ) and the number of values, n , that are averaged in each sample. Furthermore, $\sigma_{\bar{X}}$ is directly proportional to σ and proportional to the inverse of the square root of n . The control limits of the \bar{X} Charts are based upon the standard deviation of the random variable \bar{X} and are designed to result in a relatively small probability that a given value of \bar{X} is outside the limits given that, in fact, the process is in-control. If we let the lower and upper control limits be denoted by LCL and UCL, respectively, and $\alpha > 0$ is chosen such that the percentage of the \bar{X} values falling inside the limits when the process is in control is $100(1-\alpha)\%$, then:

$$LCL = \mu - z_{\alpha/2} \frac{\sigma}{\sqrt{n}} \quad (4)$$

$$\text{and } UCL = \mu + z_{\alpha/2} \frac{\sigma}{\sqrt{n}} \quad (5)$$

It is the standard case that the \bar{X} Charts are based upon limits referred to as "three-sigma" limits, where $z_{\alpha/2} = 3$, with

$$LCL = \mu - 3 \frac{\sigma}{\sqrt{n}} \quad (6)$$

$$UCL = \mu + 3 \frac{\sigma}{\sqrt{n}} \quad (7)$$

It is a frequent occurrence in sampling that the physical measurements do, in fact, follow the well-known continuous probability distribution referred to as the Normal or Gaussian Distribution, which depends strictly upon the mean and standard deviation, μ and σ , and the graph of whose probability density function is that of a bell-shaped curve, symmetric about a vertical axis through the mean, μ , and approaching the horizontal axis asymptotically as one proceeds in either direction away from the mean. We say that the random variable X is normally distributed with mean, μ , and standard deviation, σ , if the density function of X is given by :

$$n(x; \mu, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2} \left[\frac{(x-\mu)}{\sigma} \right]^2} \quad (8)$$

We shall now need two classical theorems that directly depend upon the preceding notions as follows:

The Central Limit Theorem: If \bar{X} is the mean of a random sample of size n taken from a population with mean μ and finite variance σ^2 , then the limiting form of the distribution

$$Z = \frac{\bar{X} - \mu}{\sigma / \sqrt{n}}, \quad n \rightarrow \infty$$

is the standard normal distribution

$$n(z; 0, 1) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}z^2} \quad (9)$$

Chebyshev's Inequality: The probability that any random variable X will assume a value within κ standard deviations of the mean is at least $1 - \frac{1}{\kappa^2}$.

In other words, the area under a histogram or probability density curve, that lies more than κ standard deviations away from the mean, cannot exceed $\frac{1}{\kappa^2}$, where κ is any positive constant.

In conventional probability notation, Chebyshev's Inequality translates as follows :

$$P(\mu - \kappa\sigma < X < \mu + \kappa\sigma) \geq 1 - \frac{1}{\kappa^2} \quad (10)$$

The β -risk

A β -risk is defined as the probability that an X value remains inside the control limits, given that, in fact, a shift in the mean has occurred. To investigate the β -risk is equivalent to investigating the role of the sample subgroup size.

Consider now an \bar{X} Chart for known standard deviation, σ , with an in-control state having mean $u = u_0$ and suppose that the form which the shift takes is given by the equation

$$u = u_0 + r\sigma. \quad (11)$$

Since \bar{X} is assumed to be normal, we have

$$\beta = P(LCL \leq \bar{X} \leq UCL \mid u = u_0 + r\sigma), \quad (12)$$

the conditional probability that the value \bar{X} lies between lower and upper control limits, given that the mean has shifted by $r\sigma$ units. Now, for $k\sigma$ limits,

$$LCL = u_0 - k \frac{\sigma}{\sqrt{n}} \quad (13)$$

and

$$UCL = u_0 + k \frac{\sigma}{\sqrt{n}} \quad (14)$$

Hence, if the standard normal random variable is denoted by $Z = N(z; 0, 1)$, then it is easy to see that the β -risk for a single sample is given by :

$$\begin{aligned} \beta &= P\left\{Z < \frac{\mu_0 + \frac{k\sigma}{\sqrt{n}} - \mu}{\frac{\sigma}{\sqrt{n}}}\right\} - P\left\{Z < \frac{\mu_0 - \frac{k\sigma}{\sqrt{n}} - \mu}{\frac{\sigma}{\sqrt{n}}}\right\} \\ &= P\left\{Z < \frac{\mu_0 + \frac{k\sigma}{\sqrt{n}}}{\frac{\sigma}{\sqrt{n}}} - \frac{(u_0 + r\sigma) - \mu}{\frac{\sigma}{\sqrt{n}}}\right\} - P\left\{Z < \frac{\mu_0 - \frac{k\sigma}{\sqrt{n}}}{\frac{\sigma}{\sqrt{n}}} - \frac{(u_0 + r\sigma) - \mu}{\frac{\sigma}{\sqrt{n}}}\right\} \\ &= P\{Z < (k - r\sqrt{n})\} - P\{Z < (-k - r\sqrt{n})\} \quad (15) \end{aligned}$$

It follows from this result that:

- (i) The β -risk decreases with an increase in r , the magnitude of the shift in the mean.
- (ii) The β -risk decreases with an increase in n , the sample size; and,
- (iii) The probability of not detecting a shift increases with an increase in k , the control width.

We reiterate the importance of small sample size and high sampling frequency. If sampling is done very frequently, the probability may not carry as much weight as the expected or average number of runs required before an actual detection of the shift in the mean. And, even though the probability of detection of a shift on the first sample is not

very high, rapid detection is both possible and extremely important. It is a consoling fact that \bar{X} Charts with these small sample sizes lead to very rapid detection of shifts. Employing the standard geometric distribution, one can determine the probability of detecting the shift on the k -th sample after a shift as follows:

If β is the probability of not detecting a shift on the first sample following the shift, then the probability P_σ of detecting the shift on the k -th sample (assuming independent samples) is given by

$$P_\sigma = (1 - \beta)\beta^{k-1} . \quad (16)$$

In turn, the mean or expected value of the number of samples required for detection is

$$\sum_{k=1}^{\infty} k\beta^{k-1}(1 - \beta) = \frac{1}{1 - \beta} . \quad (17)$$

One observes, then, that the expected value of the number of samples required before detection is the inverse or reciprocal of the probability of detection on the first sample following the shift.

Current Sampling Procedures

The McClellan AFB Science and Engineering Laboratory has established a sequence of procedures for determining an acceptable range for the percent recovery of spiked and spike-repeat data, with control limits established over time per analyte. When an insufficient amount of spike or spike repeat data is available, the control limits are set using pre-determined control chart factors found in Standard Methods [6]. The steps in constructing the chart, suggested by the Analytical Chemistry Section, are as follows:

- Calculate the mean recovery for each spike or spike repeat set.
- Calculate the Lower/Upper control limits (LCL/UCL) within ± 3 standard deviations over n runs, or alternatively use a Standard Table of values along with the average range.
- Calculate the Lower/Upper warning limits (LWL/UWL) within ± 2 standard deviations over n runs, or alternatively use a Standard Table of values along with the average range.
- Plot data if it occurs.
- Take action on out-of-control samples.

A series of routines have been developed by the author [5] to completely automate this procedure, not only for spikes, but also for generic data samples.

Results

As a dearth of actual raw data was available at this writing, suffice it to say that the author will demonstrate the utility of one of these routines by constructing an appropriate example and illustrating the previously developed concepts. Suppose that it is desired to know how many pounds of NO_2 are being emitted from a series of twenty smoke stacks over a twenty-four hour period in the State of California. For each stack, the total gas flow rate is to be measured by an Auto5 Sampler (or similar instrument). This sampler then reports the dry volumetric stack gas flow rate, corrected to 68 degrees F. and 29.92 inches Hg, in cubic feet per hour. The concentration of NO_2 in each stack is to be measured by an Enerac3000 Analyzer, which directly reports the parts per million of NO_2 on a dry basis. Using the Ideal Gas Law, the proper conversion factors yield, for each stack, a flow rate of NO_2 in pounds per hour. For the twenty stacks tested, the following mean flow rates were observed:

Table I

Measurements X_i , ($i = 1, 2, \dots, 20$)

0.836	0.729	0.594	0.826	0.328
0.529	0.836	0.324	0.726	0.641
0.439	0.671	0.728	0.816	0.493
0.779	0.803	0.657	0.738	0.620

X_i = Pounds/Hour of NO_2 Generated by Smokestack i Over 24 Hours, $i = 1, \dots, 20$.

The Z-SCORE Z_i for an element X_i is the number of standard deviations which X_i is above or below the mean value.

Table II

DISTRIBUTION OF "Z-SCORES" FOR 20 VALUES OF X :

Rank				
R(i)	X_i	Z_i	\bar{X}	σ
1.)	.836	1.151	.66	.16
2.)	.836	1.151	.66	.16
3.)	.826	1.087	.66	.16
4.)	.816	1.023	.66	.16
5.)	.803	.940	.66	.16
7.)	.738	.525	.66	.16
8.)	.729	.468	.66	.16
9.)	.728	.462	.66	.16
10.)	.726	.449	.66	.16
11.)	.671	.098	.66	.16
12.)	.657	.009	.66	.16
13.)	.641	-.093	.66	.16
14.)	.620	-.227	.66	.16
15.)	.594	-.393	.66	.16
16.)	.529	-.808	.66	.16
17.)	.493	-1.038	.66	.16
18.)	.439	-1.382	.66	.16
19.)	.328	-2.090	.66	.16
20.)	.324	-2.116	.66	.16

Table III

STATISTICAL ANALYSIS OF THE RANDOM VARIABLE, $X = \langle X_i \rangle$

Mean	Variance	Standard Deviation	Mean Deviation
.66	.025	.16	.13

In the parlance of Chebyshev's Theorem :

- At least 15 of the 20 sample points lie in the closed interval : [.342, .969].
- At least 18 of the 20 sample points lie in the closed interval : [.185, 1.126].
- At least 19 of the 20 sample points lie in the closed interval : [.029, 1.283].
- At least 19 of the 20 sample points lie in the closed interval : [-.128, 1.439].
- At least 19 of the 20 sample points lie in the closed interval : [-.285, 1.596].

The MINIMUM	= .32
The MAXIMUM	= .84
The RANGE	= .51
The MID-RANGE	= .58
COEFFICIENT OF SKEWEDNESS	= -.82

(Measurements Rounded Down)

Table IV

NOTE: Mean = μ , Standard Deviation = σ

σ	$\mu - 3\sigma$	$\mu - 2\sigma$	$\mu - \sigma$	μ	$\mu + \sigma$	$\mu + 2\sigma$	$\mu + 3\sigma$
.16	.19	.34	.50	.66	.81	.97	1.13

LCL = 0.55 and UCL = 0.77

Table V

FREQUENCY DISTRIBUTION FOR THE RANDOM VARIABLE, X

NOTE1: $F(k)$ = Frequency of Element k

NOTE2: $P(k)$ = Relative Frequency of Element k

$\longleftrightarrow P(X = k)$ for the Random Variable, X

NOTE3: $T(k) = 1 / P(k)$

**\longleftrightarrow Avg. # Elapsed Elts. Per Occurrence of Element k
(Measurements Rounded Down)**

Index	1	10	17	3	19	2	9	20
k	.84	.32	.33	.44	.49	.53	.59	.62
$F(k)$	2	1	1	1	1	1	1	1
$P(k)$	.10	.05	.05	.05	.05	.05	.05	.05
$T(k)$	10	20	20	20	20	20	20	20

Index	18	12	7	14	11	5	16	4
k	.64	.66	.67	.73	.73	.73	.74	.78
$F(k)$	1	1	1	1	1	1	1	1
$P(k)$	.05	.05	.05	.05	.05	.05	.05	.05
$T(k)$	20	20	20	20	20	20	20	20

Index	8	15	13
k	.80	.82	.83
$F(k)$	1	1	1
$P(k)$	.05	.05	.05
$T(k)$	20	20	20

LCL = .551

UCL = .761

LWL = .586

UWL = .726

* Denotes Measurements Falling Outside the Range of the CONTROL LIMITS

[LCL,UCL] :

1.) *	.836
2.) *	.529
3.) *	.439
4.) *	.779
5.)	.729
6.) *	.836
7.)	.671
8.) *	.803
9.)	.594
10.) *	.324
11.)	.728
12.)	.657
13.) *	.826
14.)	.726
15.) *	.816
16.)	.738
17.) *	.328
18.)	.641
19.) *	.493
20.)	.620

The Process is OUT-OF-STATISTICAL-CONTROL, as $11 / 20 = 55.00\%$ of
the Measurements Fall Outside the Range of the CONTROL LIMITS [LCL,UCL] :

.836	.529	.439	.779	.836	.803	.324	.826	.816	.328	.493
------	------	------	------	------	------	------	------	------	------	------

Now, instead of sampling the entire set of 20 variates, consider selecting

FIVE SAMPLE SUBGROUPS of size FOUR, as follows:

Subgroup I:	0.836	0.529	0.439	0.779
Subgroup II:	0.729	0.836	0.671	0.803
Subgroup III:	0.594	0.324	0.728	0.657
Subgroup IV:	0.826	0.726	0.816	0.738
Subgroup V:	0.328	0.641	0.493	0.620

An analysis of each subgroup similar to that performed on the entire
20-variate sample yields the following results (rounded down) :

Subgroup I: 0.836 0.529 0.439 0.779

Mean = μ , Standard Deviation = σ

σ	$\mu - 3\sigma$	$\mu - 2\sigma$	$\mu - \sigma$	μ	$\mu + \sigma$	$\mu + 2\sigma$	$\mu + 3\sigma$
.17	.15	.31	.48	.65	.81	.98	1.14

LCL = .397 UCL = .895 LWL = .480 UWL = .812

The Process is IN-STATISTICAL-CONTROL, as NO ELEMENTS Fall Outside

the Range of the CONTROL LIMITS [LCL,UCL] :

The MEDIAN	=	.65
The MEAN	=	.65
The MINIMUM	=	.44
The MAXIMUM	=	.84
The RANGE	=	.40
The STANDARD DEVIATION	=	.17
PEARSONIAN COEFFICIENT OF SKEWEDNESS	=	-.15

NOTE: Subgroup I Generates an Essentially NORMAL DISTRIBUTION.

Subgroup II: 0.729 0.836 0.671 0.803

Mean = μ , Standard Deviation = σ

σ	$\mu - 3\sigma$	$\mu - 2\sigma$	$\mu - \sigma$	μ	$\mu + \sigma$	$\mu + 2\sigma$	$\mu + 3\sigma$
.06	.57	.63	.70	.76	.82	.89	.95

LCL = .663 UCL = .856 LWL = .696 UWL = .824

The Process is IN-STATISTICAL-CONTROL, as NO ELEMENTS Fall Outside

the Range of the CONTROL LIMITS [LCL,UCL] :

The MEAN	=	.76
The MINIMUM	=	.67
The MAXIMUM	=	.84
The RANGE	=	.17
The STANDARD DEVIATION	=	.06
PEARSONIAN COEFFICIENT OF SKEWEDNESS	=	-.29

Subgroup III: 0.594 0.324 0.728 0.657

Mean = μ , Standard Deviation = σ

σ	$\mu - 3\sigma$	$\mu - 2\sigma$	$\mu - \sigma$	μ	$\mu + \sigma$	$\mu + 2\sigma$	$\mu + 3\sigma$
.15	.12	.27	.42	.58	.73	.88	1.03

LCL = .346 UCL = .805 LWL = .423 UWL = .729

The MEDIAN	= .63
The MEAN	= .58
The MINIMUM	= .32
The MAXIMUM	= .73
The RANGE	= .40
The STANDARD DEVIATION	= .15
PEARSONIAN COEFFICIENT OF SKEWEDNESS	= -.98

* Denotes Measurements Falling Outside the Range of the CONTROL LIMITS

[LCL,UCL] :

1.)	.594
2.) *	.324
3.)	.728
4.)	.657

The Process is OUT-OF-STATISTICAL-CONTROL, as $1/4 = 25.00\%$ of the Measurements Fall Outside the Range of the CONTROL LIMITS [LCL,UCL] :

Subgroup IV: 0.826 0.726 0.816 0.738

Mean = μ , Standard Deviation = σ

σ	$\mu - 3\sigma$	$\mu - 2\sigma$	$\mu - \sigma$	μ	$\mu + \sigma$	$\mu + 2\sigma$	$\mu + 3\sigma$
.04	.64	.69	.73	.78	.82	.87	.91

LCL = .709 UCL = .844 LWL = .732 UWL = .821

The Process is IN-STATISTICAL-CONTROL, as NO ELEMENTS Fall Outside

the Range of the CONTROL LIMITS [LCL,UCL] :

The MEDIAN	=	.78
The MEAN	=	.78
The MINIMUM	=	.73
The MAXIMUM	=	.83
The RANGE	=	.10
The STANDARD DEVIATION	=	.04
PEARSONIAN COEFFICIENT OF SKEWEDNESS	=	-.03

Subgroup V: 0.328 0.641 0.493 0.620

Mean = μ , Standard Deviation = σ

σ	$\mu - 3\sigma$	$\mu - 2\sigma$	$\mu - \sigma$	μ	$\mu + \sigma$	$\mu + 2\sigma$	$\mu + 3\sigma$	
.12	.15	.27	.40	.52	.65	.77	.89	

LCL = .333 UCL = .708 LWL = .396 UWL = .645

* Denotes Measurements Falling Outside the Range of the CONTROL LIMITS

[LCL,UCL] :

- 1.) * .328
- 2.) .641
- 3.) .493
- 4.) .620

The Process is OUT-OF-STATISTICAL-CONTROL, as 1 / 4 = 25.00 % of
the Measurements Fall Outside the Range of the CONTROL LIMITS [LCL,UCL] :

The MEDIAN	=	.56
The MEAN	=	.52
The MINIMUM	=	.33
The MAXIMUM	=	.64
The RANGE	=	.31
The STANDARD DEVIATION	=	.12
PEARSONIAN COEFFICIENT OF SKEWEDNESS	=	-.87

Conclusion

Accidental toxic emissions into the atmosphere must be curtailed and eventually completely eradicated. This requires a major statistical effort, due to the complexities of maintaining validity of data when samples are examined. Using the principles of probability and statistical inference, as well as, techniques of statistical quality control and assurance, this paper investigates the foundations of a sampling plan which validates the selected sample size, test frequency, and methodology to ensure that samples of the lowest volume of the total air emission field provide data which are statistically sound or valid. Control limits are used to locate and isolate abnormalities or difficulties in the sampling procedure to assist in the systematic reduction of variability and to determine if randomly collected toxic emissions data adhere to an acceptable level of quality. The method, in turn, is generalized to determine whether or not the performance of a generic production process is maintaining a standard level of quality based upon optimal sample size and frequency of sampling.

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**AN INVESTIGATION INTO CONSOLIDATING THE MACHINES IN A AND C BAYS FOR
SETTING UP MANUFACTURING CELLS IN A-BAY AT McCLELLAN AFB**

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Abstract

The economic feasibility over a planning horizon of five years is investigated for consolidating the machines currently in A and C bays of the Manufacturing Section at McClellan AFB. The investigation also includes new CNC machines scheduled to be purchased at four different times during the planning horizon. A very attractive nominal internal rate-of-return of 116.36% evaluated suggests the proposed consolidation of machines in A and C bays be undertaken. As the components produced on machines to be consolidated in A-bay are known, a significant amount of data was gathered from the databases available at McClellan AFB and analyzed to either extract or estimate usable elements of data. Such data would be used with the mathematical model proposed to be developed for converting the functional manufacturing (FM) system as it currently exists in A and C bays into a cellular manufacturing (CM) system to be located in A-bay. The fact that one or more of the operations required of some of the components can be performed on alternative machine types creates a challenging problem within the context of converting an existing FM system into a CM system. That is, the proposed model and subsequently the solution algorithm should be capable of *simultaneously* dealing with alternate routing options for the same component while identifying the component and machine assignments to individual manufacturing cells. A host of computer programs would be developed to implement the algorithmic steps on the computer to solve the entire research problem. A proposal for this part of the research would be submitted to the SREP for consideration. The methodology proposed to be developed can also be applied to similar problem environments in other Air Logistic Centers within the Air Force to substantially improve the overall manufacturing productivity.

AN INVESTIGATION INTO CONSOLIDATING THE MACHINES IN A AND C BAYS FOR SETTING UP MANUFACTURING CELLS IN A-BAY AT McCLELLAN AFB

Rasaratnam Logendran

I. Introduction

There are six divisions under the Technology and Industrial Support (TI) directorate at McClellan AFB. The Manufacturing and Services Division (TIM) is one among them. The research was conducted for the Manufacturing and Services Branch (TIMM), which is one of the five branches under TIM. This branch has two sections: Manufacturing Section (TIMMA) and the Process Support Section (TIMMB). The conventional machining area (TIMMAB) under the manufacturing section currently has machines located in two different bays; the A and C bays. The overall objectives of the research are two fold. First, to investigate the economic feasibility of consolidating the machines in A and C bays into the area in A-bay only, over a 5-year planning horizon. As the parts, subassemblies, and end items (all of them herein after referred to as components for convenience) produced on machines to be consolidated in A-bay are known, the second objective focuses on gathering all of the essential data needed to develop a model and a solution algorithm to identify the component and machine assignments to separate areas which are commonly called manufacturing cells. This part of the investigation is based on the concepts of cellular manufacturing (CM).

A five year planning horizon is used to assess the economic feasibility of the proposed consolidation, with start and end dates of July 1, 1995 and June 30, 2000. Some of the machines in both A and C bays are too old, and are thus highly inefficient. Included in the consolidation plan is the purchase of several new CNC machines that would replace some of the old machines. The new machines would improve the manufacturing productivity on the shop floor considerably for several reasons. First, a move toward CNC is a step in the right direction because it is the state-of-the-art for the 90's and beyond. Second, the setup time required to process components on a CNC machine would be considerably lower than that on a conventional machine, thus resulting in substantial savings. This is due to being able to use modular fixturing with CNC machines. Modular fixture for processing a component on a CNC machine can be made by assembling two or more pieces, selected from a pool of pre-fabricated fixtures. At the present time as modular fixtures are not used, fixtures of different sizes and capabilities are made all a new as and when they are needed, thus requiring longer setups on machines. Finally, introducing new CNC machines into the pool would improve a host of issues related to tooling as less time would be spent looking for the items needed to setup the tooling, among others.

The purchase of new machines during the first year (July 1, 1995 - June 30, 1996) is scheduled to occur at three different times. First purchase, scheduled for 9/95, includes three CNC-turning centers at a cost of \$300K. These three centers will replace five old turret lathes currently located in A and C bays. The second

purchase of two CNC vertical-machining centers at a cost of \$300K is scheduled for 3/96. These machining centers will replace three old conventional milling machines currently located in A and C bays. The third purchase, scheduled for 5/96, will be two CNC 2-axis milling machines at a cost of \$64K. These 2-axis milling machines will replace two other old milling machines.

In addition to the three new purchases during the first year, another purchase of two CNC vertical-machining centers is scheduled for 3/98 at a cost of \$363K. In estimating the cost, the rate of inflation is accounted for as this purchase is scheduled to occur approximately three years from now. At that time, these vertical machining centers will replace one rotary milling machine and another conventional milling machine currently located in A and C bays. These four purchases over a five year period (July 1995 - July 2000) would constitute to four of the five negative cash flows. The fifth negative cash flow represents the cost incurred in consolidating the machines currently in A and C bays, scheduled for 7/95. The factors that contribute to this cost include moving, rewiring and restringing of machines. The estimated cost of the consolidation is \$20K. As all of the machines will be located in A-bay after consolidation, it is estimated that considerable time will be saved due to not having machinists move from C-bay to A-bay or vice versa. Additionally, with the current arrangement considerable time is spent by machinists in A-bay by walking over to speak with the Foreman, whose office is located in C-bay. The estimated saving per month is \$6,446. The first savings is realized in 7/95 and will continue to be realized each month thereafter until the end of June in year 2000 as shown in the cash flow diagram (Figure 1). The actual predicted output is based on an average hourly rate of \$21.25 per hour per machinist including fringe benefits, for 28 machinists each spending 1/2 hr. per person per day for a total of 260 work days in a year.

The total workload over a period of 8 months (October 1994 to May 1995) is used to evaluate the average monthly workload. It turns out that the average monthly workload is 5538.81 hours. It is also estimated that 5 turret lathes currently in A and C bays account for 25% of the average monthly workload recorded on the shop floor, which is 1385 hrs. The purchase of 3 new CNC-turning centers is estimated to provide a 20% increase in capacity (277 hrs./month) over the time accounted by the turret lathes. A shop rate of \$80.39/hr. is currently used for work carried out on all the machines on A and C bays. The factors used by the accounting department at McClellan AFB in determining this rate include, depreciation of machinery, support provided by both planning and scheduling staff, and the employees' rate of pay. For a shop rate of \$80.39/hr., this translates into a monthly saving of \$22,268. As the purchase of the 3 CNC-turning centers is scheduled for 9/95, the first monthly savings will be realized in 10/95 and will continue to be realized each month thereafter until the end of June in year 2000 as shown in Figure 1. The actual predicted output after introducing the 3 CNC-turning centers would be 5815.81 hrs./month.

The 2 new CNC vertical-machining centers, scheduled to be purchased in 3/96, would replace 3 old conventional milling machines. It is estimated that the old milling machines account for 25% of the total workload (1,454 hrs./month), which is the same percentage of workload accounted for the 5 old turret lathes when they are turned in on 9/95. The reason is that the milling machines are used more frequently

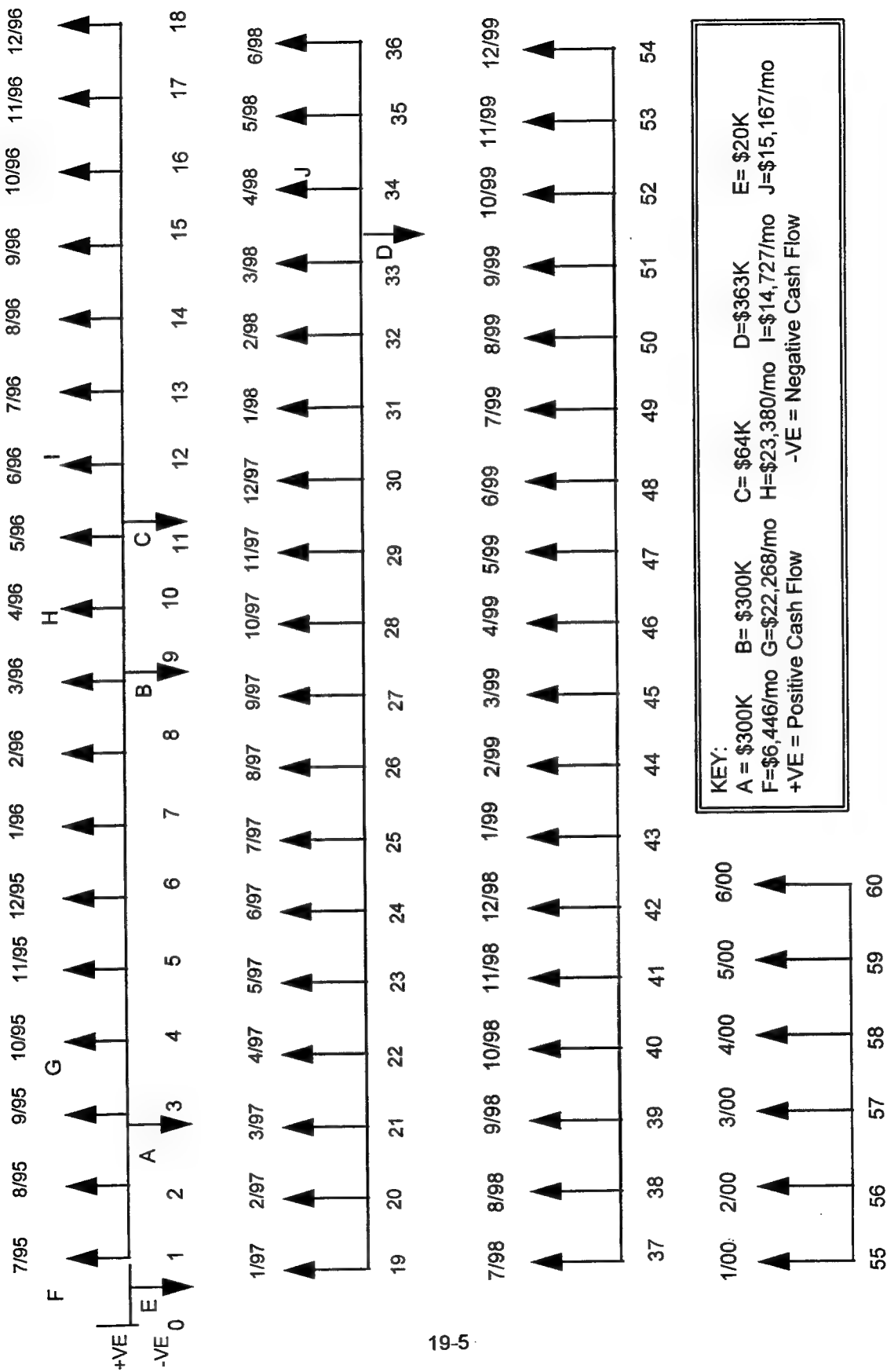


FIGURE 1: Cash Flow Diagram Over a Planning Horizon of Five Years

than the turret lathes, thus accounting for about the same percentage of workload generated, although the former is fewer in numbers. The estimated savings due to increased capacity by introducing the 2 new CNC vertical-machining centers is 20% of the workload accounted for by the 3 old milling machines, which is \$23,380/month. The first monthly savings due to the purchase of 2 CNC vertical-machining centers will be realized in 4/96 and will continue to be realized each month thereafter until the end of June in year 2000 as shown in Figure 1. The actual predicted output after introducing the 2 CNC vertical-machining centers would be 6106.67 hrs./month.

The 2 new CNC 2-axis milling machines, scheduled to be purchased in 5/96, would replace the 2 old conventional-milling machines. It is estimated that the old milling machines account for 20% of the total workload (1221.33 hrs./month). The estimated savings due to increased capacity by introducing the 2 CNC 2-axis milling machines is 15% of the workload accounted for by the 2 old milling machines, which is \$14,727/month. The first monthly savings due to the purchase of 2 CNC 2-axis milling machines will be realized in 6/96 and will continue to be realized each month thereafter until the end of June in year 2000 as shown in Figure 1. The actual predicted output after introducing the 2 CNC 2-axis milling machines would be 6289.83 hrs./month.

The final purchase of 2 new CNC vertical-machining centers will be made in 3/98. These machines will replace one rotary milling machine and another conventional milling machine that would likely be highly inefficient at that time. The two old milling machines are estimated to account for 20% of the total workload (1257.97 hrs./month). It is estimated that 15% of the workload accounted for by the 2 old machines would be saved by introducing the 2 CNC vertical-machining centers due to increased capacity. The savings is evaluated to be \$15,167/month, based on a shop rate of \$80.39/hr. The first monthly savings due to the purchase of 2 CNC vertical-machining centers will be realized in 4/98 and will continue to be realized each month thereafter until the end of June in year 2000 as shown in Figure 1.

II. Net Present Worth Analysis

The cash flow diagram is now complete with all of the negative and positive cash flows identified at the right time they are scheduled to occur over a 5-year planning horizon. It is important to perform a thorough economic analysis to determine if the estimated expenses coupled with savings do in fact produce an acceptable internal rate of return (IRR) that would make the proposed consolidation a viable alternative, worth undertaking. A net present worth (NPW) analysis is carried out to evaluate the IRR for the proposed consolidation as shown below.

Assuming an interest rate of i %/month, the NPW (in ' 000s) for the 5-year period can be evaluated as:

$$\begin{aligned} \text{NPW} = & -20 + 6.446 (P/A, i, 60) + 22.268 (P/A, i, 57) * (P/F, i, 3) \\ & - 300 (P/F, i, 3) + 23.380 (P/A, i, 51) * (P/F, i, 9) - 300 (P/F, i, 9) \\ & + 14.727 (P/A, i, 49) * (P/F, i, 11) - 64 (P/F, i, 11) \end{aligned}$$

$$+ 15.167 (P/A, i, 27) * (P/F, i, 33) - 363 (P/F, i, 33)$$

A trial interest rate of $i = 5\%$ gives a NPW of 377.23K.

As an interest rate of 5% gave a +ve NPW, an interest rate higher than 5% is tried in the hope of evaluating a -ve NPW so that an appropriate IRR for the proposed consolidation can be evaluated by interpolation.

An interest rate of $i = 10\%$ gives a NPW of -24.36K.

Interpolating between 5 and 10%, gives an $i = 9.967\%$. As i is an interest rate assumed on a monthly basis, the nominal annual IRR for the proposed consolidation over a 5-year period is 116.36%. A nominal IRR of 116.36% is by any standards a very attractive rate of return. Thus, it is suggested that the proposed consolidation of machines in A and C bays be undertaken.

III. Designing Manufacturing Cells in A-Bay

The components processed on machines currently located in A and C bays can be broadly classified into three groups: Non-programmed, Mistr/Routed and Cost Class 4.

A. Non-Programmed Components

Non-programmed work constitutes to part of the work received from outside. There were over a thousand non-programmed components produced during the past year (July 1, 1994 - June 30, 1995) that have had one or more operations performed on the machines in A-bay and/or C-bay (TIMMAB). The ownership for these components is either with the conventional machining area (TIMMAB) or any other section within the Manufacturing and Services Division (TIM). Of the over thousand different components produced, the ownership claimed by TIMMAB was for 29, 60, 31, 22, 21, 37, 24, 15, 17, 6, 11 and 49 during the months of July 1994 through June 1995 respectively for a total of 322 components. The decision as to which section should claim ownership for a component produced is made by the planning department, and is dependent upon a number of factors, including the total number of operations performed and the workload contributed by each section. In general, the ownership for a component lies with the section that contributes to the largest workload.

Even including the different types of non-programmed components for which TIMMAB has had ownership in the research poses a problem. As they are non-programmed, very seldom is the production of a component in this class is repeated within a one-year period. Every component requested by the customers is usually different, and therefore carry different part numbers. Because they are different, the routings on these components are different as well. In other words, it is very likely that in the next year a whole new set of components which belong to the non-programmed class is produced on the machines currently in A and C bays. In the analysis focusing on the conversion of an existing functional manufacturing (FM) system into a cellular manufacturing (CM) system, the components to be included should have stable demand pattern over the planning horizon. Only then the workload generated on machines, and the total

moves representing the material handling necessary would be representative of the components produced in the proposed CM system. To maintain a stable demand pattern, the production of the same components should be repeated in the future. In light of these factors, the components that belong to the non-programmed class are excluded to perform a meaningful analysis of the proposed CM system.

B. Mistr/Routed Components

The components that belong to the Mistr/Routed class are generally produced in each of the four quarters of the year. The demand for these components is fairly stable over a period of one year and are very likely to be repeated in the future. Thus the components in the Mistr/Routed class is a good candidate to be included in the investigation of the proposed conversion from a FM system to a CM system for the machines planned to be consolidated in A-bay. Some of the components in this class have fixed routings. That is, each operation required of them would be performed on a unique machine (type). The operations required of the remaining components are fixed. However, one or more of these operations can be performed on more than one machine type. At the present time, several factors determine which machines should be used to process a Mistr/Routed component. These include, but not limited to, the availability of machines, the capabilities of the machinist who happens to be available at that time concerning whether or not the individual is proficient in operating the machines called for by the component as per the routing information, among others. Having alternative machine types for one or more operations on some of the components creates a challenging problem within the context of converting an existing FM system to a CM system. That is, if a model and a solution algorithm were developed to solve the problem, those should be capable of simultaneously dealing with alternate routing options for the same component while identifying the component and machine assignments to individual manufacturing cells.

To the best of the author's knowledge, an investigation into a cell formation problem, simultaneously focusing on the assignment of components and machines to manufacturing cells in the presence of alternative machine options for operations required of some components, has not been previously reported in published literature. There is clearly a need to determine a unique machine type for performing the operations required of each component that would provide the best component and machine assignments to individual manufacturing cells. Besides determining the best component and machine assignments to individual manufacturing cells, at the present time, the decisions made in TIMMAB concerning which machine option to use for performing the operations required of the components are based on ad-hoc rules and past experiences.

To address this need, first a mathematical model, capable of determining a unique machine type for performing the operations required of each component as well as the component and machine assignment to individual manufacturing cells, would have to be developed. However, to develop the model a suitable planning horizon must be selected. One can consider using a planning horizon of 6-months to include only the first acquisition of 3 new CNC-turning centers, scheduled for 9/95. To solve the research problem

completely, however, a solution algorithm for solving the proposed model would have to be developed and implemented on a computer. It means that fairly detailed computer programs would have to be written to execute the specific steps associated with the solution algorithm in order to deal with several components currently produced on the machines in A and C bays. This part of the research will be further investigated and a proposal will be submitted to the Summer Research Extension Program (SREP) for consideration. It also means that when the programs are written and implemented to obtain the desired results, it would be time to include the second and third acquisitions in the analysis. At that time, a similar exercise should be performed to investigate the impact of all three machine acquisitions. Thus, it would only be logical to assume a planning horizon of one year to include the first three acquisitions of machines.

Each component that belongs to the Mistr/Routed class may be produced several times per year, and the number of units produced each time may be different. To carry out an accurate analysis, it is important to evaluate an average processing time for performing each operation required per unit of a component. The records maintained on the computer system at McClellan AFB show the standard time for processing a unit of each component. Often, however, the standard processing time shown represents performing a group of operations. For example, if a component had five operations required to be performed, then the standard processing time for performing all five operations may have been aggregated and given. Or, the five operations may have been divided into two sets (three in the first and two in the second for instance), and the aggregated standard processing time for performing each set may have been evaluated and given.

Data in this form is not usable in this research. To further complicate issues, not all of the operations required of a component are performed on a machine currently in A-bay or C-bay. If one of the operations required of a component is just cleaning, for example, it would not need a machine. To carry out an accurate analysis, the estimated processing time for these operations should be excluded from the investigation. Thus a thorough study was conducted to identify the actual operations required to be performed on machines in A and C bays for each component. Based on the detailed discussions with the Shop Work Leader, the setup time on a machine for processing a component was estimated. Using the number of times each component is produced per year, the number of units produced every time the machine is setup, and the average batch size produced during the planning horizon, an average setup time per unit of a component is evaluated. Also, an average run time per unit of a component is evaluated by dividing the estimated total run time for producing a component over the planning horizon by the total number of units produced. The average processing time per unit of a component on a machine can be evaluated as the sum of the average setup and run times evaluated per unit as described above.

C. Cost Class 4 Components

The work undertaken in the Cost Class 4 category is generated from within the base itself. In other words, the customers in this class are other units in the TI directorate including the conventional machining area (TIMMAB) which is solely responsible for the machines currently located in A and C bays. A wide

variety of work is carried out in this category, ranging from repair to making a whole new fixture or tool; might be required by the other unit. As the customer is internal, the information maintained on the computer for the type of work undertaken in this group is not quite as detailed as that maintained for the other two groups. The total workload generated on machines currently in A and C bays in each of the past eight months (October 1994 - May 1995) has been 5877, 5693, 5519, 4870, 4952, 6413, 5326, and 5660 hrs. respectively. In each of those eight months, the workload generated by cost class 4 has only been 373, 122, 75, 131, 119, 37, 74, and 47 hrs. respectively. Based on these numbers, the cost class 4 work evaluated as a percentage of the total work load in each month is 6.35, 2.14, 1.36, 2.69, 2.40, 0.58, 1.39, and 0.83% respectively. This averages out to 2.20%, which is very small compared to the workload generated by the other two categories (non-programmed and Mistr/Routed). Thus, the cost class 4 type work is excluded from the analysis of component and machine assignments to individual manufacturing cells.

IV. Problem Description and Motivation

The problem at hand focuses on the conversion of an existing FM system as it currently exists in A and C bays into a CM system proposed to be laid out in A-bay. Ideally, when manufacturing cells are setup, the processing requirements of parts assigned to a cell would be met by machines assigned to the same cell (King 1980; Chan and Milner 1982; Waghodekar and Sahu 1984; Seifoddini and Wolfe 1986; Kumar et al. 1986; Kusiak 1987; Ballakur and Steudel 1987; Askin and Subramaniam 1990; Harhalakis et al. 1990; Logendran 1990, 1991; Logendran and Ramakrishna 1995a). For a problem of this magnitude, one can expect with almost certainty that this would not be the case. In other words, quite a number of components assigned to a cell would require processing on one or more machines assigned to other cell(s). The components that require processing on machines assigned to other cells are referred to in literature as bottleneck components and machines that perform such operations are called bottleneck machines (Vannelli and Kumar 1986; Kumar and Vannelli 1987; Seifoddini 1989; Kern and Wei 1991; Logendran 1992; Logendran and Ramakrishna 1993; Logendran and Ramakrishna 1994, 1995b). The assignment of components and machines to individual manufacturing cells should, therefore, focus on minimizing the intercell moves (movement by components between cells) generated by all of the components. Although intercell moves is a major contributor of reducing manufacturing productivity, intracell moves (movement by components between machines assigned to the same cell) also play a role. Thus, for a comprehensive analysis, the total moves should be evaluated as a weighted sum of inter- and intracell moves (Logendran 1990, 1991). Based upon the discussion the author has had with the Shop Foreman, normalized weights of 0.8 and 0.2 would be used in this research for inter- and intracell moves respectively.

The available capacity of machines to be included in the analysis is sufficient to carry out the operations required of parts. However, certain machine types have more than one unit. There would be 16 different machine types, including the 3 new types of CNC-machine purchases scheduled for 9/95, 3/96, and 5/96

as shown in Table 1. Of the 16 types, 12 have multiple units, ranging between 2 and 8. The total number of units of machines included in the problem is 41, including the 7 new units to be purchased during the one year period (July 1, 1995 to June 30, 1996). Thus, it is important to identify each unit of a machine type as a separate entity. If a component was produced in a quarter, it would have required the machines needed for

Table 1. Machine Types included in the Investigation

TYPE	DESCRIPTION	NUMBER OF UNITS	IDENTIFIER
A	Vertical Mill - 1	2	A1, A2
B	Small Lathe	3	B1, B2, B3
C	Chucker Lathe	1	C1
D	Engine Lathe - 1	8	D1, D2, D3, D4, D5, D6, D7, D8
E	Rotary Mill	5	E1, E2, E3, E4, E5
F	Horizontal Mill	3	F1, F2, F3
G	Jig Bore - 1	2	G1, G2
H	Universal Mill	2	H1, H2
I	Vertical Mill - 2	3	I1, I2, I3
J	Jig Bore - 2	1	J1
K	Engine Lathe - 2	1	K1
L	Engine Lathe - 3	1	L1
M	Shot Peener	2	M1, M2
N	CNC Turning Center (purchase date: 9/95)	3	N1, N2, N3
O	CNC Vertical Machining Center (purchase date: 3/96)	2	O1, O2
P	CNC 2-Axis Milling Machine (purchase date: 5/96)	2	P1, P2

production be setup during that quarter. The number of batches produced of a component per year is equal to the number of quarters the component was produced during the one year period. Thus, the number of moves generated by a component between machines over the planning horizon is assumed equal to the number of batches produced per year.

Based on the discussions held with the Shop Foreman, it is determined the maximum number of machines that can be accommodated in a cell is 8. All of these requirements would be factored into as separate constraints in the model yet to be developed.

V. Analysis of Data and the Identification of Constraints

A large amount of data for the Mistr/Routed components produced during July 1, 1994 - June 30, 1995 was gathered from the existing databases at McClellan AFB. There were nine different sections which had ownership for a total of 91 components included in the research. Of the nine, seven were outside of TIM. Because most of the data obtained was not in usable form, a significant amount of time was spent on discussing jointly with the Shop Work Leader to analyze the data gathered from the databases to either extract or estimate usable elements of data. Such elements include:

- a. The annual demand for each component during the planning horizon is stable and equal to the annual demand during the previous year (July 1, 1994 - June 30, 1995).
- b. The machine type or types where each operation required of a component can be performed.
- c. The shop is open 8 hrs./day, 5 days a week, and 52 weeks/yr. Thus, each unit of a machine type has a capacity of 2080 hrs./yr. As some machine types have multiple units, the total available capacity of a machine type per year is equal to number of units * 2080.
- d. The average processing time required to perform a specific operation per unit of a component on a machine type (s). The description on how this time is evaluated is given in Section III.B.

The following constraints were identified as appropriate to be included in the model to be developed for the research problem. These are verbal descriptions only. The challenge would to be develop the mathematical representation of the constraints, resulting in a constraint set necessary for the mathematical model. The objective function of the model would focus on minimizing the total moves evaluated as a weighted sum of both inter- and intracell moves generated by all components. First, each component must be assigned to a cell. Similarly, each unit of a machine type must be assigned to a cell. Each operation required of a component must be performed on one of the (say) c cells considered appropriate for the research problem. Having two or more units for some machine types as shown in Table 1 presents an interesting scenario. Under these circumstances, the available capacity of a machine type assigned to a cell must be greater or equal to the workload generated by all of the components. Finally, the maximum number of machine types assigned to a cell must be less than or equal to the predetermined maximum

number as described in Section IV.

VI. Conclusions

The research undertaken at McClellan AFB has led to investigating a real, yet challenging problem. The investigation would be continued by the author to develop a suitable mathematical model and a solution algorithm. A host of computer programs would then be developed to implement the algorithmic steps on the computer to solve the entire research problem. A proposal for this part of the research would be submitted to the SREP for consideration. The end result of this research would be the identification of cell assignment for the components and machines in the area in A-bay, and the routings for the components that would result in substantial increase in manufacturing productivity. The solution to be identified can be implemented in the manufacturing section (TIMMA) at McClellan AFB. To the best of the author's knowledge the problem investigated, dealing *simultaneously* with alternative machine options and the assignment of components and machines to individual manufacturing cells has never been reported in published literature. Thus, the methodology proposed to be developed can be applied to similar problem environments in other Air Logistic Centers within the Air Force to substantially improve the overall manufacturing productivity.

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INVESTIGATION ON SCHEDULING ISSUES
UNDER MANUFACTURING ENVIRONMENT
AT MANUFACTURING AND INDUSTRIAL SERVICES DIVISION
OF MCCLELLAN AIR FORCE BASE

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Abstract

Under manufacturing environment, the efficiency of our operations is the key to meet cost, schedule and performance commitments. In this paper, investigations on scheduling issues were conducted at the manufacturing and industrial services division. The current scheduling practices at machine shops, paint shop and T38 windshield frame production are studied. Shortcomings of manual scheduling and advantages of using a scheduling software are addressed. Then a windows-based user-friendly scheduling software is presented. The software employs scaling neural network algorithm developed by the author with improvements to handle parallel machines, operation-split/operations-combined situations.

Two examples are shown in detail. As a result, it is recommended that all shops and all operations use Gantt charts to create job charts and schedule charts in order to optimize efficiency and productivity. After successful installation of a paper-based system, scheduling software with optimization capability is proposed.

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INTRODUCTION

The Air Force is getting smaller and budgets will continue to be reduced in response to the changing world environment. However, the goals, satisfying our customers' needs in war and peace, enabling our people to excel, sustaining technological superiority, enhancing the excellence of our business practices and operating quality installations, have to be met.

The development of schedules is a problem in almost every field. Scheduling problems are common, but solutions which optimize efficiency are not. In manufacturing, scheduling resources and tasks for maximum efficiency is a universal problem.

So far, there have been no overall solution to manufacturing scheduling problems. Due to the increase in flexible manufacturing, the need to address more complex scheduling problems is again drawing the attention of industry researchers. The demand for new short term solutions and approaches is necessary.

Neural networks simulate some of the functions in the biological nervous system and provide a new approach to attack complex combinatorial optimization problems through their intrinsic parallelism and heuristic nature. This is the approach applied and will be discussed in more detail in later section of this paper.

A Scaling Neural Network (SNN) [1] for the job-shop scheduling problem has been developed by the author. Comparisons

have been made with different neural network configurations, and with the conventional heuristics of priority dispatching rules. The above pilot work of neural networks approach to job-shop scheduling showed that SNN is superior to other neural networks and outperforms conventional heuristics statistically [2].

The SNN algorithm is being applied to applications at machine shops and a specific project "T38 windshield frame production". The results of this research indicate that the SNN algorithm is applicable in real industrial environment and that economic impact is definite.

However, there is a serious gap between a useful algorithm and its practical application in the industry. It involves two issues:

1 The current manual scheduling practice is diverse. The data format employed at different shops is not uniform so that it is not yet ready to meet the data entry requirement of a software.

2 The software is not yet user-friendly. Unless the software to implement the algorithm is very user-friendly, no one will use the program even if it is good.

This paper consists of two parts. The first part discusses the shortcomings of the current manual scheduling practices and then recommends the Gantt chart as a tool for improvement and preparation for the future use of a scheduling software. The second part proposes a windows-based user-friendly scheduling software with a neural network optimization algorithm.

DISCUSSION OF THE PROBLEM

TIM is a manufacturing and services division at the McClellan Air Force Base. Under TIM, there are five sub-divisions. Each sub-division may have about ten shops or projects. For example, there are conventional machine shop, numerical controlled machine shop, tools/fixture shop, paint shop and so on within one sub-division; there are also many special projects under sub-divisions,

one of which is the T38 windshield frame production.

Let's investigate the current scheduling practices of the above mentioned four shops in detail, then generalize.

Conventional machine shop

There are forty-five machines, such as, mills, grinders, lathes, drills, sanders, saw and so on. There are about twenty-six machine operators working one shift every day. The work orders come from planner/scheduler's office with a priority number. The supervisor of the shop is the one who assigns jobs to the machine operators. Currently he assigns jobs day by day. In other words, the machine operators only know today's jobs, but not tomorrow's. There are a few measures, for example, effectiveness, overtime, etc., to judge the overall performance of the shop. Looking at the past data, overtime is well within the expected range. However, effectiveness, defined as earned hours over actual hours, shows the fluctuation: sometime only around 65% though many times above 90%.

Numerical controlled (NC) machine shop

There are thirteen machines of mills and lathes. There are twenty-four machine operators working two shifts every day in addition to three programmers. Again, the supervisor of the NC shop assigns jobs to machinists. Some tasks can either be performed by the machines in NC machine shop or the machines in the conventional shop.

Paint shop

Paint shop is a little bit different from the above two shops. It is a support shop. The orders with work control documents drop in at two specified spaces, one for large parts, the other small

ones. Then the supervisor of the shop assigns jobs to workers. There are four paint booths accommodating different size parts to be painted.

T38 windshield frame production

It is a dedicated shop for a particular product. The scenario then is different from a general shop. However, there are work rooms, equipment, tools, operators, and work control documents.

T38 windshield frame is a product with many parts assembled together. Some parts, for example, hinges and shoes, are made by general shops. Some equipment, for example, autoclaves and ovens, are shared by other products. Like any other products, there is an engineering specification process plan which describes the detailed process steps in sequence to be performed. The current operations are organized as being assigned by the supervisor to three crews, each of which consists of about ten people.

Concerns

Although supervisors of each shop are trying their best and are doing a reasonably good job now, the following concerns should be addressed.

1 People-dependent

The supervisor of each shop does the scheduling manually without a software tool. The rules how to schedule are in his/her mind. The solution totally depends on him/her. If for some reason a supervisor asks his back-up to perform his task, everything will be somewhat different if not a mess because no two persons can schedule identically.

2 Optimal solution

There are always a few scheduling constraints, such as limited number of machines or operators. Because of doing it manually, a supervisor can only schedule orders according to priority number,

then take care of those constraints. Our brain's capability is limited to play too many parameters at the same time. As a consequence, the schedule solution usually is only feasible and by no means of optimal.

3 Simulation and analysis

To do a better job, we would like to see constraints ahead of time. We like to have alternative schedule to make comparisons and to do analysis. What if we could simulate a situation. What if we could tie schedule, machine utilization, production backlog and earned hours together!

4 Easy to manage data

All the shops are not completely independent. For example, some machines in the conventional machine shop and numerical controlled machine shop have similar capability so that some parts can either be made in the conventional shop or numerical controlled shop in case one shop is overloaded or a machine breaks down. Some parts of the T38 windshield frame are made by other shops. Therefore there is connection between different shops. We need a customized database to support shop floor scheduling. The format employed at different shops should be the same so that the data and information can be shared.

Recommendations of scheduling format

A shop floor parts tracking system with scanning bar code is in the process of development, which tracks parts of T38 windshield frame as a test product. The system will be applied to all the shops to track parts at the end of the first phase. At the second phase, a good scheduling algorithm hopefully will be incorporated into the system, making it not only track parts but schedule when and where to operate parts optimally. To meet such a goal in the future, we need to prepare a uniform scheduling practice at all the shops now.

Even scheduling manually at present, it is good to show jobs and resulting schedule clearly. The Gantt chart format is recommended here to be employed at all shops.

Essentially, there are two charts, one is the problem, i.e., job chart, the other is the solution, i.e., schedule chart.

Use an actual paint job as an example (it was picked up randomly). The routed order with sequence number 60394 came on July 6, 1995. The parts are Flap Tracks. They are to be taped first, then painted, to wait to dry, to be removed tapes, finally stamped and put in pallet boxes ready to be shipped.

Currently, the AFMC 137 Form is served as a work control document. The order with that form comes in unexpectedly. So does the finished job: the customer has to drop in to check if it is done. The workers do not know the schedule either. The order comes when it comes, the job is done when it is done. The above order with a supposed due date July 21, 1995 is still in the process on Aug. 9, 1995. (The reason for the delay is not shown explicitly on the 137 form.)

The following describes the recommended method to organize job orders for this example.

In the job chart, one line is corresponding to that job. That line may consist of a few blocks. In this example, it may have six blocks. The first block is its control number or sequence number as in the 137 form, the next few blocks indicate the operations in sequence. Therefore, the second block will be tape, the third paint, the forth dry, the fifth remove tape, the sixth ship. In addition to what operation will be performed, the processing time it takes will be shown in each block. Of course, the operation itself gives information where (a machine or a room) the part will be performed. For example, the operation "paint" may mean "paint booth two" because it will be painted in Booth Two. The suggested job chart is drawn in the following diagram.

Job Description	Operation# Control #	1	2	3	4	5
J1	123456	Tape 4 hrs	Paint 2 hrs	Dry 8 hrs	Remove 2 hrs	Ship 1 hr
J2						
J3						

Figure 1 The proposed Job Chart

PAINT SHOP	Mon. 12345678		Tues. 12345678		Wed. 12345678		Thur. 12345678		Fri. 12345678	
Tape		J1								
PB1			J1							
PB2										
PB3										
PB4										
Dry			J1							
R-Tape					J1					
Ship						J1				

Figure 2 The proposed Schedule Chart

The proposed schedule chart is described in Figure 2. The above paint problem is used again. At the top of the chart, there is a time line. B is the abbreviation of paint booth. R-Tape means "remove tape". Ship includes stamping operation. J1 is Job 1.

These two charts are supposed to be posted on the bulletin board. Then not only the supervisor but all the workers know what jobs they have and how they are assigned. The task of tracking parts is fulfilled too for in the schedule chart when and where of the parts are clearly indicated. Customers can know when they can expect their orders completed by looking at the chart.

Similarly, all the other shops can and should use these two kinds of charts. This information, i.e., the job orders and the assignments, should not be solely in the shop supervisor's mind. It should be easily viewed by other people, for example, the shop supervisor's supervisor, the supervisor of other shops, and the workers who are team players too.

The above recommendation will ease the transition from scheduling manually to the next phase: developing a network software system to track parts and to generate an optimal schedule scientifically and the above two charts automatically.

The shop floor parts tracking system is in the process of development. So, only a scheduling algorithm and a windows-based user-friendly software will be discussed in the next part of this paper.

APPROACH: WINDOWS-BASED SOFTWARE

The software has to be user-friendly so that little instruction is required. Windows-based software has such a feature. A simple set of Windows skills, such as clicking mouse buttons, selecting text, and using menus, will allow operators to use the software with no training.

Other criteria

1 Database interface

A database should be employed as an interface between the software and scheduler to make data entry and communication a lot easier.

2 Optimization capability

The software is supposed to give an optimal scheduling solution instead of just a feasible one. The main purpose to have this software is not only to make the job more convenient but to improve productivity.

3 Simulation and analysis capability

It is good to do analysis on capacity, machine utilization, earned hours, backlog orders, etc., when adding or removing a machine. It requires the software have simulation capability.

The following figures from 3 to 5 illustrate the design and key features of these windows of the software.

Figure 3 shows the menu and tool bar of the software. File, Window and Help are pretty much of standard function. Edit is used to input information to job table, line table, machine table, operation table and secondary machine table. Also, under Edit, Non-working Days makes schedulers conveniently determine working days or non-working days. View gives functions to look at these tables, view schedule of operations aligned along machines or jobs. Option offers a choice of machine lines, priority rules, problem sizes, and shifts. Schedule is to run the software to generate a schedule for a given problem. Figure 4 illustrates an operation table, which contains the key information to run a schedule. Figure 5 gives the job chart and the schedule chart of 6/5 job-shop problem. In practice, these charts are colorful. Different color of these operations block corresponds to different operation, which makes it easy to recognize them. The software is designed to be very user-friendly. For example, double clicking the operation

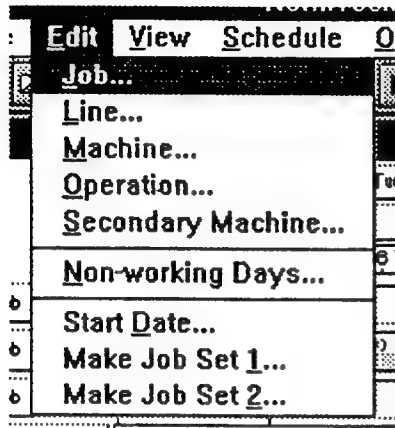


Fig.3 Menu of the proposed software

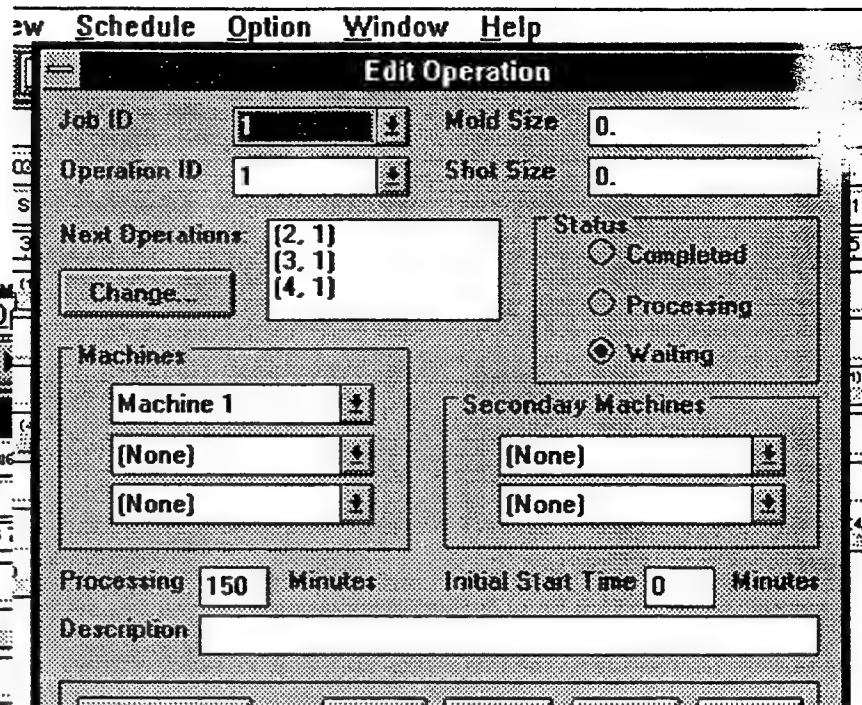


Fig.4 Operation Table of the proposed software

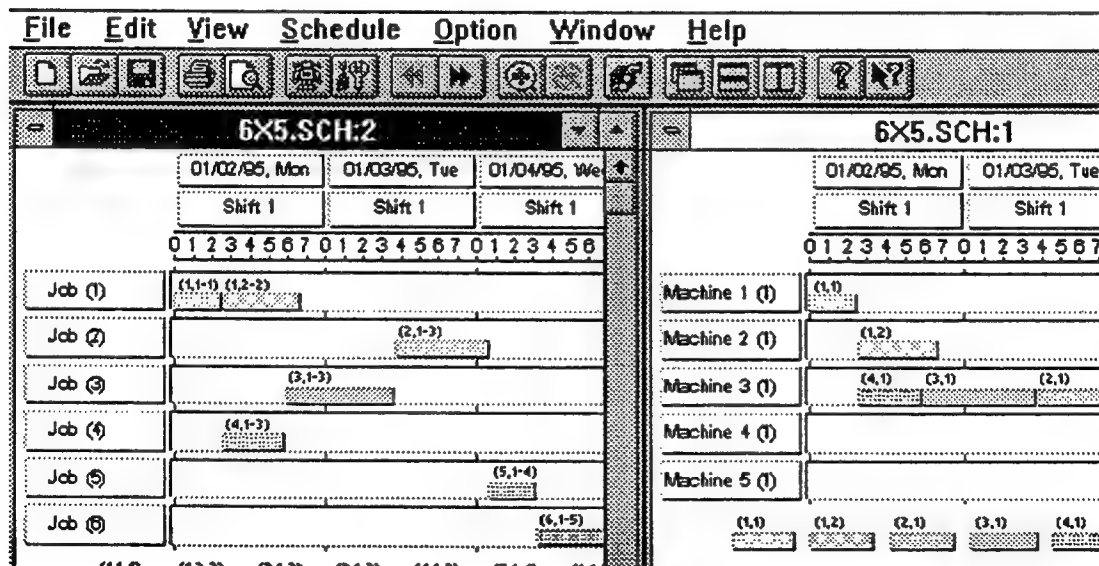


Figure 5 Job and Schedule Charts generated by the software

block in schedule or job charts will pop up the Job & Operation table which gives one the necessary information about a job and operation.

Neural networks algorithm

The Hopfield neural networks have optimization capability. The neural networks algorithm employed is the Scaling Neural Networks (SNN) which is a modification of Hopfield's. The configuration of SNN can be found in "A Neural Network Approach to Job-Shop Scheduling" by Norman D. Zhou, etc [3].

There are four significant improvements which make the SNN work in the real shop floor environment.

1 Machine utilization

In practice, one of the goals is to increase the utilization of machines in addition to achieving a shorter completion time to meet customer's due date.

To achieve this goal, jobs are put into two sets according to due date: Job Set 1 and Job Set 2. Job Set 1 is run by the SNN algorithm first to generate an optimal schedule. However, there are still idle times of machines. Then Job Set 2 is run to fill in these gaps as many as possible. One SNN algorithm is run twice. The only difference is that the starting times of the operations in Job Set 1 are fixed in the second run.

2 Parallel (identical) machines

There are identical machines in shop floor. For example, there are a few mills and a few lathes with the same specifications. The improved SNN can handle such situation easily with the same goal in mind: to minimize the completion time of jobs.

3 Operation-split case

The original SNN like the other neural networks or conventional algorithms assumes that every operation only has one

subsequent operation. In reality, it is possible to have a few operations not start until one specific operation is completed. On the job-shop problem chart, one operation leads not only to one but to several operations. The improved SNN can work gracefully with this operations-split situation by modifying a constraint term in the energy function of the SNN algorithm.

4 Operations-combined case

Of course, operations-combined problems happen very often in practice. For example, operations are combined when two parts are assembled together.

This situation is equivalent to having several pre-operations instead of only one pre-operation for every operation in the job-shop problem chart. The improved SNN can solve operations-combined problems neatly.

The above four important improvements are not discussed in detail here because of the length of the paper. It will be addressed and illustrated in future publication. The rest of this paper will show two example problems and the corresponding outcomes solved by the proposed software. The first example is a classic job-shop problem in a text book "Theory of Scheduling" by R.W.Conway, etc [4]. The second example is a real production problem at TIM of McClellan Air Force Base.

Examples

1 A classic 5/3 Job-shop problem under conventional machine shop environment

Figure 6 is a 5/3 job-shop problem, i.e., five jobs and three machines. Job 1 consists of three operations, job 2 four operations, Job 3 three operations, Job 4 four operations and Job 5 two operations. In the operation box, there are two numbers, the first representing machine # to indicate on which machine the operation will be performed, and the second number the processing

time of the operation.

Figure 7 is the solution of the above 5/3 job-shop problem; whose operation blocks are rearranged into rows by machine numbers.

The two numbers in the block represents job # and operation # respectively. The block length represents the processing time, then the total horizontal length is the completion time of that machine, and the largest completion time of all the machines will be the completion time of the job set.

The schedule of Figure 7 generated by the proposed the software is an optimum solution which gives the shortest completion time to finish the job set and can not be further improved for there is no idle time on machine 3.

It takes time in the order of seconds for the software to find the solution. It may take days for manual scheduling to find the optimum solution for this 5/3 job-shop problem if it is found eventually. In practice, optimization is not taken when scheduling manually and the software gives a near-optimum (optimal) or optimum solution.

2 A model of scheduling T38 windshield frame production

T38 windshield frame production is a complicated project. It mainly consists of four parts: Bulkhead doubler, Innerskin, Outerskin & Arch, and Fairing. The current fabrication process flow chart is strictly sequential: 18 steps for the bulkhead doubler fabrication, 30 the innerskin, 83 the outerskin & arch, 22 the fairing, and 45 steps for the windshield frame assembly. These flow charts describe the engineering specification process plan. However, these steps, namely operations, are not necessarily taken sequentially. In fact, some of them are performed in parallel. Therefore, the above recommended job charts and schedule charts are necessary for the scheduling purpose.

According to the format of the job chart recommended, the major operations of T38 windshield frame production can be

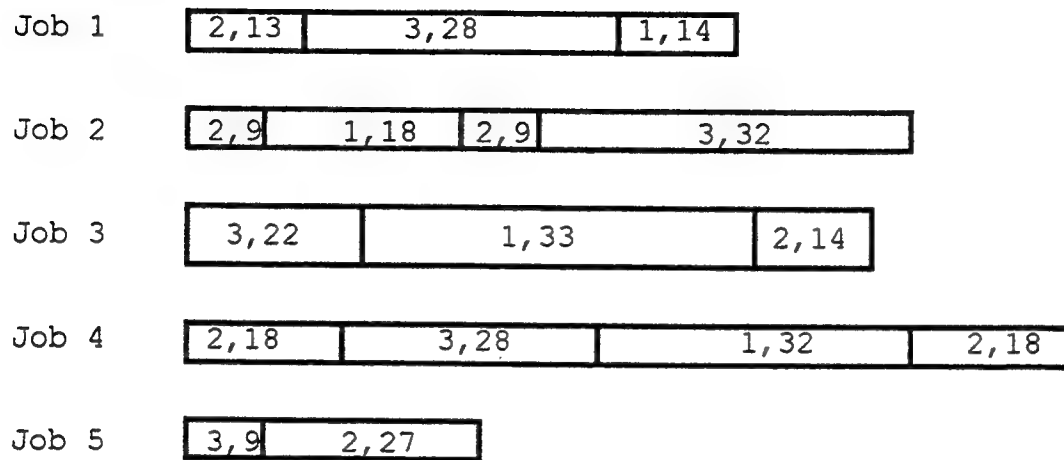


Figure 6 A 5/3 job-shop problem

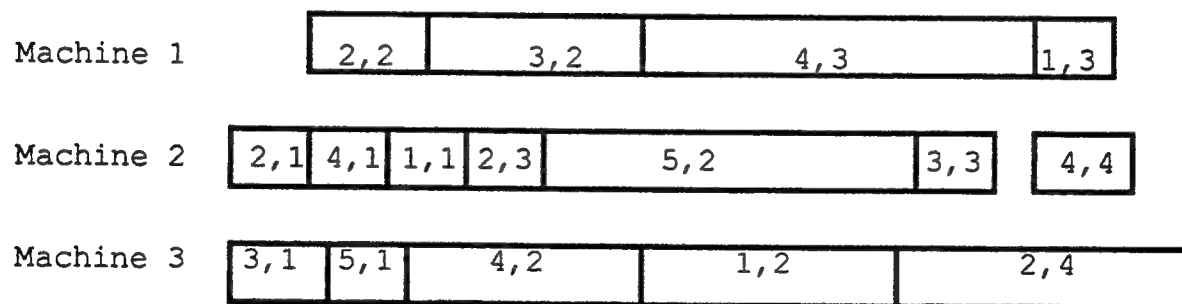


Figure 7 A 5/3 job-shop solution (optimal schedule)

described in Figure 8.

There are about thirty people involved in the project. They are organized as three major teams: one of eight workers for the fabrication of outerskin & arch, one of ten workers for the innerskin, bulkhead and fairing, and one of six workers for the frame assembly. In addition to these three teams, there are workers to cut and label plies continuously for use by these three teams, and to kit the assembled product for shipping. By assigning different number of people to different teams, the work leader is trying to make full use of his manpower.

By using the proposed scheduling software, the scheduling chart is made as Figure 9. This time, jobs are scheduled to five

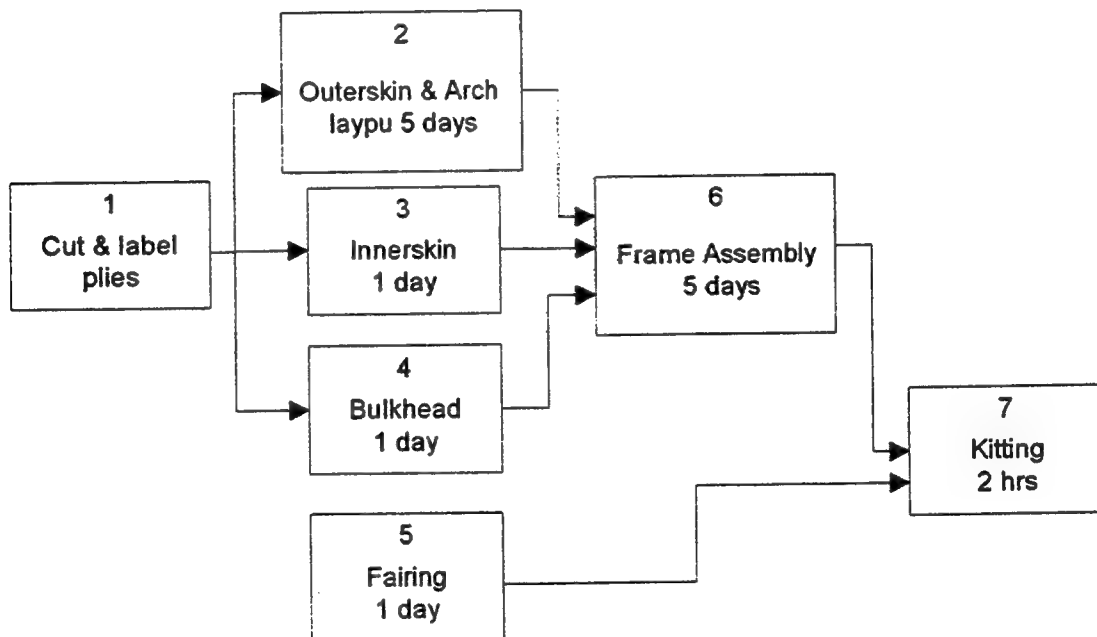


Figure 8 Description of T38 Windshield Frame Job

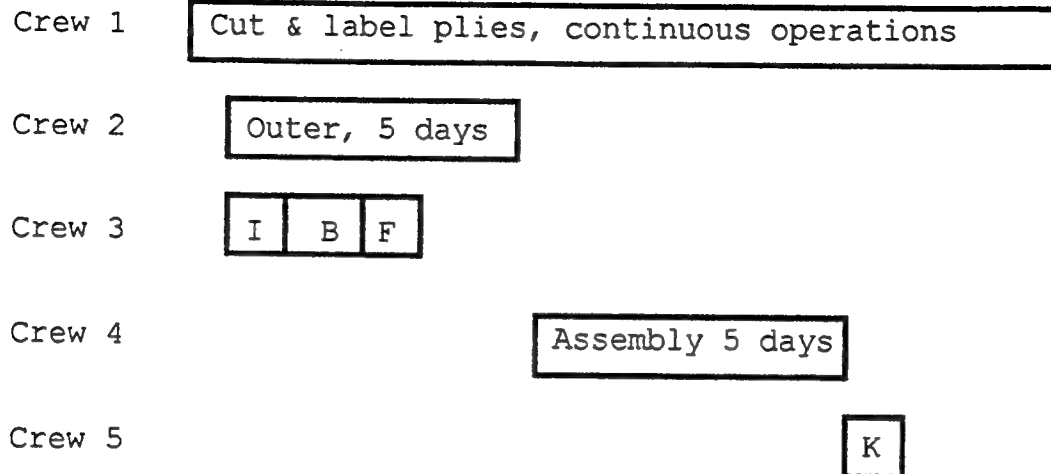


Figure 9 Schedule for T38 Windshield Frame Job

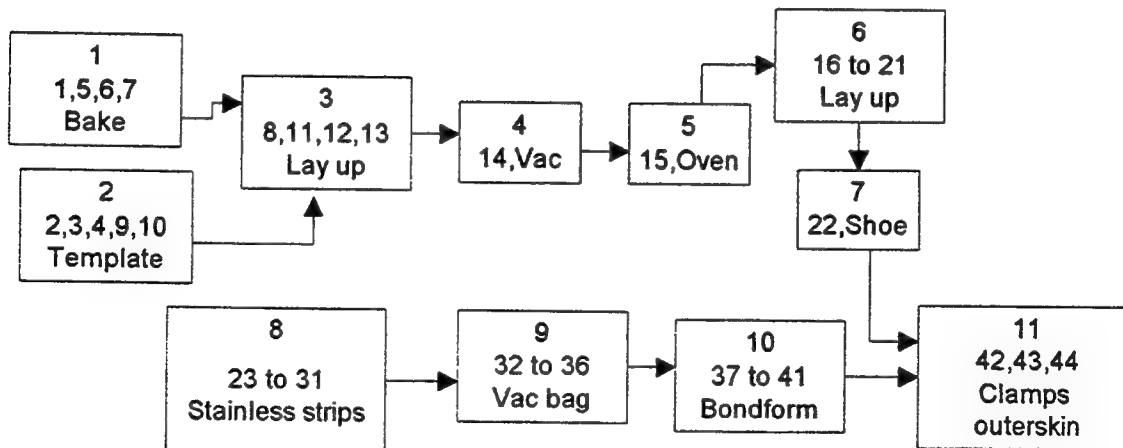


Figure 10 A job chart for Outerskin & Arch layup

crews as is organized. In the figure, outer is outerskin & arch operation, I represents innerskin, B bulkhead, F fairing and K kitting operation. This example is served as a case in which operators are key instead of machines. Of course, a case with mixed machines and operators can be run too.

Big operations can be broken down to small operations. Use Outerskin & Arch operation with five days processing time as an example. According to the 83 sequential blocks in the process flow chart for the outerskin fabrication, a job chart of the first 44 steps can be made as shown in Figure 10. The numbers in the blocks are the steps' number. A few steps are combined together into an operation block based on the key facilities/operators involved. For example, the oven has to be available for the Bake block, the vacuum bag system for the Vac block, and aluminum shoes ready for the Shoe block. (Since the example is to introduce the concept how to make job chart, only the first 44 steps are used, and they could be combined differently in practice by the more experienced work leader.) A schedule chart similar to the previous two examples then will be mapped out by the software.

There are other support shops, machine shops and other facilities (e.g., ovens and autoclaves) involved and shared by other jobs. The schedule chart shows the operations during these five days explicitly to other operators (e.g., autoclave operator) so that they will know when and where to do what too. If this complicated job can comply with the job and schedule chart format, so can every job. As a result, economic benefits may come along. For example, there are four autoclaves now, and two new autoclaves are coming. If all the jobs are scheduled as recommended, it is possible to optimize the use of autoclaves. Simulations can be performed and analysis can be done to know the impact if more machines or operators are added.

CONCLUSION

The current scheduling practices at the manufacturing and services division at McClellan Air Force Base are manual. In order to improve efficiency and productivity, two phases of improvement are recommended. At the first phase, a paper-based system will be implemented by using Gantt chart format for job charts and schedule charts at all shops and for all operations. Then a scheduling software with user-friendly windows-based features and optimization capability will be tailored to the practical manufacturing environment and be applied.

ACKNOWLEDGEMENT

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**A Feasibility Study for Re-Manufacturing Aircraft Structural Components
Using Laser Scanning and X-Ray Computed Tomography**

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A Feasibility Study For Re-Manufacturing Aircraft Structural Components Using Laser Scanning And X-Ray Computed Tomography

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Abstract

In the past few years, non-contact digitization systems have become a very popular means to rapidly re-manufacture commercial products, molds and dies, and industrial parts. This popularity can be attributed to continual improvement in the accuracy and reliability of these systems. In this study, a feasibility was initiated to investigate the re-engineering and re-manufacturing capabilities of two non-contact digitization techniques, laser scanner and X-Ray computed tomography and to evaluate the feasibility of using these techniques to reduce part turnaround time at Warner Robins Air Logistics Center. The study includes an in-depth survey of two state-of-the-art laser scanning systems, along with re-engineering and re-manufacturing practices with these systems. The significant findings from this study include the following :

- Laser scanning technologies have matured to a stage that they can capture and reproduce intricate surface details typically present in the aircraft structural components.
- Laser scanning technologies, through both re-engineering and re-manufacturing approaches, can dramatically reduce part turnaround time and skill levels required to re-manufacture aircraft structural components at WR-ALC.

¹ Ramesh M. C. is a graduate student at Georgia Tech who assisted Dr. Joe Chow in conducting the laser scanning project during Summer 1995.

A Feasibility Study For Re-Manufacturing Aircraft Structural Components Using Laser Scanning And X-Ray Computed Tomography

Joe G. Chow and Ramesh M. C.

Introduction

The goal of this project is to investigate the current capabilities of the laser scanning and X-Ray computed tomography (X-Ray CT) technologies, and study the technical and economic feasibility of implementing one or both technologies for reverse engineering aircraft structural components at Warner Robins Air Logistics Center (WR-ALC).

WR-ALC is one of the five ALCs of the United States Air Force (USAF). Its primary responsibility is to manufacture spare and replacement aircraft structural parts for the USAF. A majority of the machined structural components are characterized by volumetric features such as slots, deep pockets and cavities, and the demand for these components is typically in small quantities. Normally, WR-ALC aims to re-manufacture parts within tolerances ($\sim 0.010''$) without any design modifications or analysis.

Currently, manufacturing a part at WR-ALC involves manual creation of a CAD surface or solid model, process planning, NC code generation, fixture design, and finally machining of the part. Though all the parts that need to be manufactured are accompanied by two-dimensional (2D) part drawings, and in most cases, a copy of the actual part is also available, a CAD model of the part rarely exists. The 3-D CAD model needs to be manually created from the 2D drawings or by directly measuring the part. This process is usually the most time-consuming portion of the entire manufacturing process.

The 3-D CAD model is the source for many subsequent operations. Once the surface or solid model of the part is created, other activities can benefit greatly. The model can be used during process planning to determine the number of machining operations and select the machine and

cutting tools, and machining parameters (feed, speed, depth of cut, etc.) for each operation. The NC toolpaths for each machine operation can then be generated using CAM software. The fixtures for holding the part during each operation are then designed and fabricated. Fixture elements can be displayed along with the part model for fixture design verification and interference checks.

Currently, at WR-ALC, all the activities in the manufacturing process are performed manually with the aid of computers. Due to the extent of human involvement, it requires on an average six weeks to manufacture parts of medium complexity. In the case of high complexity parts, the turnaround time may take as long as several months. To increase combat readiness and sustainability, it is essential for WR-ALC to reduce part turnaround time and cost. This requires automation and/or elimination of some of the steps in the manufacturing process.

Since CAD model creation constitutes a major portion of the turnaround time, maximum returns can be obtained by increasing the efficiency of this process. The primary aim of this study is to investigate the feasibility of using non-contact digitization techniques to reduce the model creation time (or completely eliminate it from the manufacturing cycle) for parts to be re-manufactured, thus decreasing the overall turnaround time for manufacturing aircraft structural components.

Re-Engineering and Re-Manufacturing

While the normal manufacturing process involves machining of the part from the CAD model, re-engineering (also known as reverse engineering) involves creation of a CAD model from the actual part [1]. In re-engineering, the surfaces of the part are digitized using Coordinate Measuring Machines (CMMs), laser scanning or other digitizing techniques. The point data (also called point cloud data) obtained is then used to create a surface or solid CAD model for the part. This model is used to redesign the part, if necessary, and then manufacture the part. The CAD model can also be used to perform other design and manufacturing functions as shown in Figure 1.

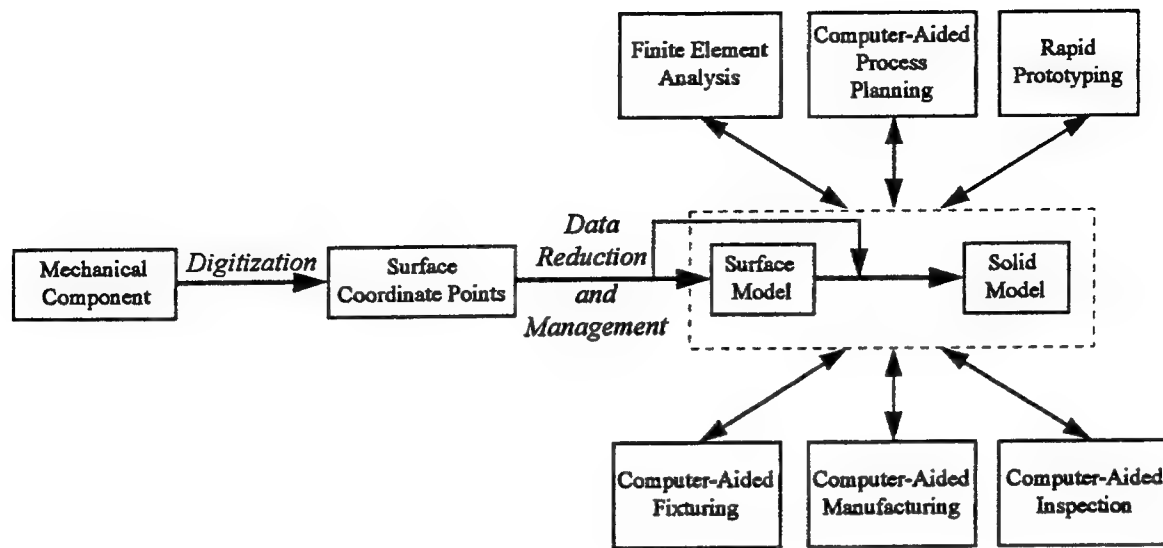


Figure 1: Re-engineering Methodology

Re-manufacturing is different from re-engineering in that its main goal is to duplicate an existing part without design modification or analyses. In this approach, after digitizing the surfaces of the part, NC toolpaths are generated directly from the point cloud data and are used to machine the part. By eliminating the model creation step, part turnaround time is greatly reduced. Thus, re-manufacturing has a distinct advantage over re-engineering if only part duplication is desired. However, since both re-manufacturing and re-engineering involve digitization of the part's surfaces, understanding and acquisition of digitization capability is the first and foremost requirement.

Digitization Techniques

Digitization is the process of obtaining the coordinates of points on the surface of the part. Digitization techniques can be divided into two categories, contact and non-contact techniques.

The most popular contact method is through the use of a CMM, wherein a mechanical touch probe is used to obtain the coordinates of selected points on the surface of the part. Digitization of complex parts using a CMM has two main disadvantages: inability to digitize hard to reach spots and inability to capture very minute details on the surface of complex parts. Also, for some surfaces, the data collected may need to be compensated for stylus offsets and deflections. Fixturing of the part is also more complicated due to the probe's mechanical contact with the workpiece. The biggest drawback, however, is that, compared to non-contact techniques, it is a much slower digitizing process, especially for complex parts.

Non-contact techniques eliminate most of the problems associated with contact methods. Though many non-contact digitization techniques are rapidly emerging in the marketplace, the most popular and proven technologies are laser scanning and X-Ray CT. While both these technologies have their advantages and disadvantages, both techniques are effective re-engineering tools (with digitizing accuracy on the order of 0.001") and have the potential to drastically reduce the turnaround time at WR-ALC. In this section, both these technologies are discussed briefly.

Laser Scanning

Laser scanning is a non-contact digitization procedure that provides fast and consistent acquisition of component geometry data through the use of a laser beam [2]. In laser scanning, the Z-axis values are measured on a grid of predetermined X and Y coordinates. The basic elements of the system are: a non-contact laser probe which emits a low energy laser beam, a scanning mechanism to project the laser beam onto the surface being digitized and optic receptors with collecting lenses for detecting the reflected laser beam. The 'Z' coordinate of each point on the part surface is calculated by trigonometric algebra applied to the projection direction (scanner angular position) and the detection direction made by the light spot position on the sensor with the principal point of the collecting lens. Figure 2 shows the basic elements of a laser scanner.

In this process, each surface of the part is separately scanned and point cloud data is obtained. In the case of re-engineering, the point cloud data for all the surfaces are merged to get a single point cloud for the entire part. This point cloud is then used to develop the CAD model of the part. Toolpath generation and machining is carried out using this CAD model. In the case of re-manufacturing, the point cloud data for each surface is used to directly generate NC toolpaths for that surface. The part is then machined using these toolpaths.

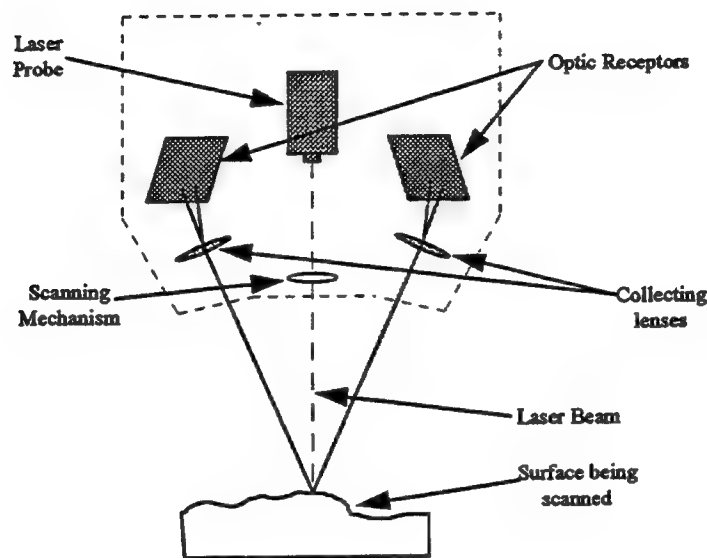


Figure 2: Laser Scanning System

X-Ray Computed Tomography

X-Ray CT is a powerful non-contact inspection and digitization technique that was conceived in the early 1960s and has been developed rapidly ever since. Unlike laser scanning which is used primarily for geometry acquisition, X-Ray CT has been used in the past mainly for non-destructive evaluation such as first article inspection and failure analysis. It is only in the past few years that the technology is being used for geometry acquisition in reverse engineering applications.

The X-Ray CT geometry acquisition process begins with the entire part being scanned all at once. A 3D series of images are generated by the scan, one cross-sectional slice at a time. The distance between the slices is chosen by the operator based on the amount of detail required. Outlines of the surfaces intersected by each CT slice plane are generated using automated edge finding routines. These outlines are basically in the form of point cloud data and can be downloaded to specialized point processing software. By combining all the 2-D slices, a CAD model can be created, the process being similar to CAD model creation from laser scanned data. However, unlike laser point cloud data, the scan data from X-Ray CT cannot be directly used to generate NC toolpaths, since the point cloud data is for cross-sectional slices of the part rather than the surface.

The main advantage of X-Ray CT is its ability to capture the internal features of a part, which is impossible with laser scanning. In fact the geometry of each individual part of a complex assembly can be obtained, even if the individual parts are made from different materials. While scanning of parts with internal features such as undercuts, can prove to be a challenge for laser scanning, it poses absolutely no problem for X-Ray CT. Another important advantage of X-Ray CT is that the entire geometry of the part, regardless of complexity can be obtained in one scan. This is because X-Ray CT is performed within a known 3D space, such that all positions in the object are known relative to a common origin. Thus, the scanning process for X-Ray CT eliminates the merging of point clouds which is required in laser scanning.

Previous Work Done by CTC

In '93-'94, Concurrent Technologies Corporation (CTC), Johnstown PA, conducted a feasibility study of re-engineering aircraft components using laser scanning for WR-ALC [3]. Though some successes had been achieved with simple parts, it was generally felt that laser scanning technologies at that time were not mature enough to provide the accuracy and consistency required to re-manufacture aircraft structural components. The study classified engineering parts with respect to re-engineering into three categories:

- Category I consisted of parts with simple linear or curvilinear 2D features where the 3D object is constructed by fully extruding these features. The bounding surfaces require simple mathematical definitions, such as planar and cylindrical equations, e.g., strut.
- Category II consisted of parts with volumetric features such as slots, steps, blind holes, irregular cavities, bosses, protrusions, and notches. The bounding surfaces require either simple or complex mathematical definitions, such as planar, cylindrical, and simultaneous high order polynomial equations, e.g., leading-edge rib.
- Category III consisted of parts with convex features without any volumetric feature definition. The bounding surfaces of these parts are generally difficult to represent mathematically and are complex equations, e.g., turbine blade and tooling block.

CTC utilized a wide range of commercial laser scanning hardware and software products to study the applicability of the laser scanning process to re-engineer and re-manufacture mechanical parts. It was found that use of laser scanning to re-engineer parts belonging to categories I and III was a relatively simple process and resulted in significant time and cost savings. However, laser scanning and the subsequent modeling of parts belonging to category II, which is the category that most aircraft structural components manufactured at WR-ALC fall into, was a cumbersome process and the level of automation achieved was low. Therefore, significant savings in time and cost were not obtained for re-engineering category II parts through laser scanning. The study concluded that re-manufacturing was not a viable option since the quality of surfaces produced by this method was unacceptable.

Present Feasibility Study

The present study was initiated as a follow-up to the work done by CTC to investigate if laser hardware and software had improved over the past couple of years and if some of the earlier problems had been overcome. The scope of our study was broadened by the inclusion of X-Ray CT. More emphasis was placed on re-manufacturing since this process has the potential for maximum reduction of part turnaround time. Since our study intends to build on the work done by CTC, only category II parts were investigated.

The feasibility study was divided into two phases. During the first phase, previous work performed by CTC was reviewed and the laser scanning and X-Ray CT technologies were studied. Sharnoa, Plymouth MI, a laser scanner vendor and Aracor, Dayton, OH, an X-Ray CT vendor were visited to study the two technologies and the operations involved. One of the findings of this phase was that the initial cost of X-Ray CT equipment was much more expensive compared to laser scanners (1.5 million vs. 0.4 million). Also, X-Ray CT equipment requires special facilities and high maintenance costs for its operation. Due to these reasons, it was decided that all future efforts should be concentrated on evaluating laser scanning.

During the second phase, the leading-edge rib used in the CTC study was selected as the test part, since it was a good representative of the medium-high complexity parts manufactured at WR-ALC . This test part was shipped to two laser scanner vendors, Laser Design Inc. (LDI), Minneapolis, MN and Sharnoa Corp., Plymouth, MI. Both these vendors were selected for our study because they both offer a wide range of state-of-the-art laser scanning equipment. Based on the characteristics and capabilities of their equipment, LDI was selected to study the applicability of laser scanning to re-engineering and Sharnoa for re-manufacturing. The work performed by these two companies and the results obtained are described in the following sections.

Re-engineering by Laser Design Inc.

The leading edge rib was scanned on a 3-axis Surveyor 2000 machine. The part was mounted on the A-stage (rotary table) with the flat end being held using toe clamps. The part was then scanned from 6 angles. Next, a tooling ball and precision 1,2,3 block was mounted on the part with the 1,2,3 aligned with the system axes. The tooling ball was scanned, and its center computed using LDI's laser software Datasculpt.

The part was then removed and refixtured to the A-stage so that the original mounting surface could be scanned. An alignment relative to the original alignment was achieved by using the 1,2,3 block to set the alignment. The tooling ball was again scanned in the new position and its center again computed. Next the original mounting surface was scanned.

The scanned point cloud data was now imported into Datasculpt for processing. The data collected during the first orientation was rotated around the center of the A-stage by the appropriate amount. Data collect in the second orientation was rotated 90 degrees around the Y axis and translated in X,Y,Z until the tooling ball centers aligned.

Blending and merging of the data collected at the various angles and orientation was the next procedure. Some data clean-up and corner sharpening was also required. The final data processing in Datasculpt involved splitting the data in locations logical for surface modeling. These locations are almost identical to boundary curves/edges for each surface seen in the wire frame model.

Next an IGES file was created and exported to the CAD software 'Camax' for surface modeling. The surface were created patch by patch. For each patch, the points were first connected into lines or splines. The lines and/or splines were then connected to form a surface patch. The wire frame representation of the surface model created for the leading edge rib is shown in Figure 3. The times required to construct the model include: 18 hours for scanning, 16 hours for editing data, and 16 hours for model creation.

The reconstructed surface model was compared to the exact CAD model (which was manually created at WR-ALC) by two different methods. In the first method, the reconstructed model was imported into the 'CADD5-4X' software and superimposed on to the exact model. Both the models were visually inspected for discrepancies. It was found that there were no visual discrepancies between the two models. In the second method, the 'Measure' command in the 'Surfcam' software was used to determine some of the dimensions on the reconstructed model and these dimensions were compared to the original dimensions on the 2-D drawings of the part. The errors obtained were of the order of 0.005", which are well within the desired tolerances (0.010").

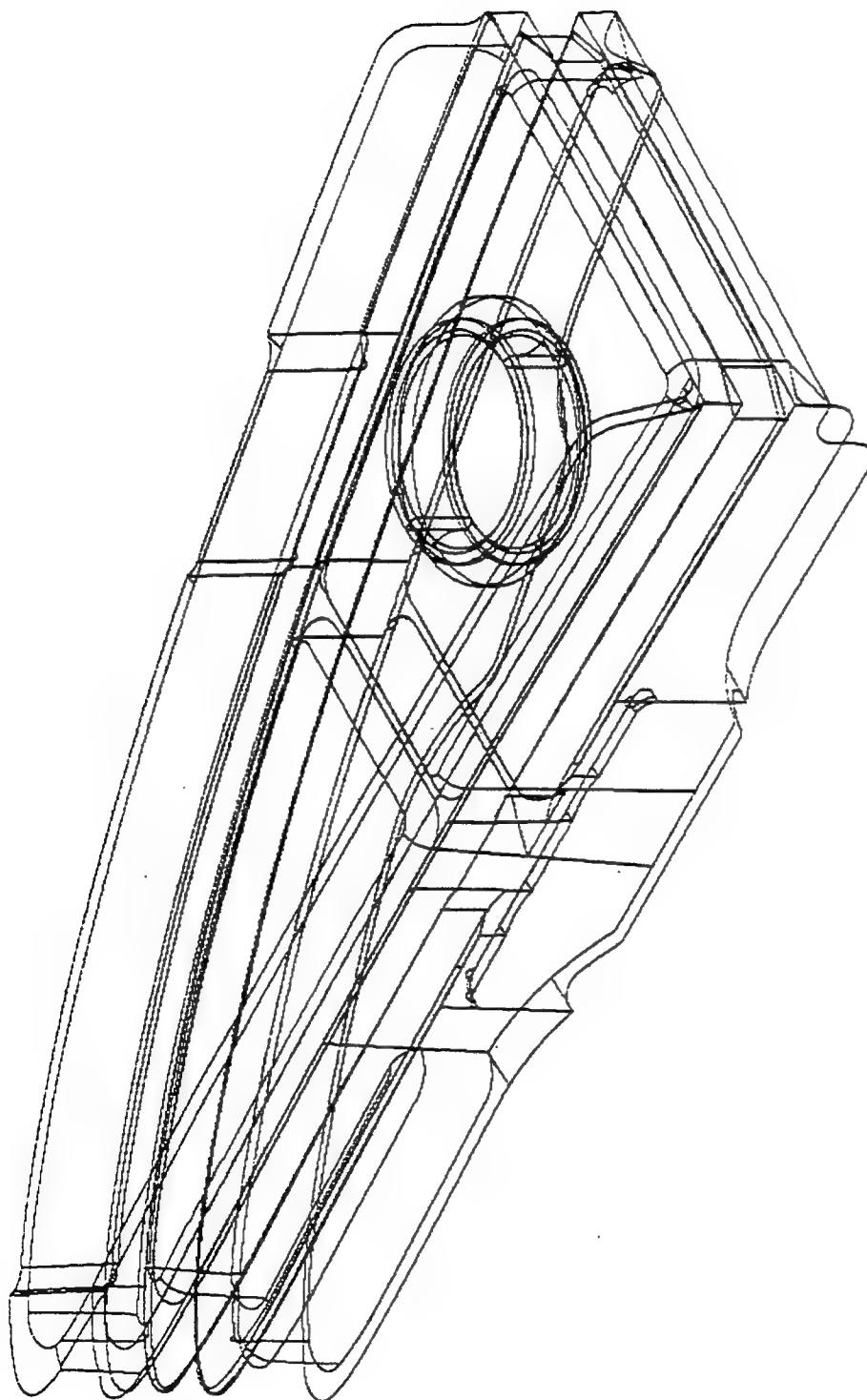


FIGURE 3. The Surface Model Reconstructed from the Scan Data

Re-manufacturing by Sharnoa Corp.

The objective of re-manufacturing is to rapidly duplicate parts that do not require any design modifications. With the modern laser scanners, the grid size for scanning is so dense (as small as 0.001" x 0.001") that the scanner can capture even the minutest details on the surface of the part. This unique capability of state-of-the-art laser scanners allow toolpaths to be generated directly from the scan data. During machining, the cutting tools follow the same path as the laser heads except with much larger stepovers, thereby resulting in duplication of the original part's surface. Thus, the most time consuming step of the manufacturing process, i.e., model creation, is eliminated.

At Sharnoa, three of six sides (top, bottom, and shallow side) of the leading edge rib were scanned and machined using machinable wax. The digitizing process began with selection of the surface to be scanned first and proper setup. The part was coated with Magnaflux developer powder to ensure that the reflectivity was even throughout the surface of the part. A master polygon, delineating the area to be digitized, was first established on the surface to be scanned. Within the master polygon, the user defined a digitizing grid, i.e., the distances between points and slices. The fineness of the grid was determined by the amount of geometric detail needed. If there are areas on the part surface that have a great deal of detail, windows with finer grid patterns can be established, thus saving time and ensuring collection of the right amount of data. The unattended scanning session was then activated. Starting from the definition of the master polygon, the entire process was repeated for the remaining two surfaces.

At the end of scanning, point cloud data was obtained for each of the three scanned surface. The Sharnoa software was used to verify if there were any irregular points in the point cloud, in which case they were either edited out or modified. The Sharnoa software also possesses editing capabilities such as scaling, merging, translation, mirroring, male-female conversion and data smoothing, which can be used to manipulate the point clouds.

After satisfactory point cloud data was obtained, toolpaths were generated for the cutters. The Sharnoa laser software could perform tool compensation for a variety of tools such as ball nose, bull nose, and flat end cutters. The user can chain files for compensation, define stock for roughing and finishing operations, and toolpaths for all the surfaces of the part can be generated directly from the point cloud data. Postprocessing tools are also normally built into the system software which allows the data to be post processed for a variety of machines and machine controllers.

The Sharnoa software provides on-screen graphic simulation for all the generated toolpaths and calculates the time required for each operation. Milling operations may be chained and run unattended. After the first surface was roughed, semi-finished, and finished, a new setup was performed for machining the next surface. This process is repeated until the third surface was machined.

The scanning and machining times for these three surfaces is provided in Table 1.

	Bottom (hrs)	Side (hrs)	Top (hrs)
Scanning setup	0.5	1	0.5
Scanning	2.5	6	2.5
grid size ($\times 10^{-3}$)	8x8	4x4	8x8
File processing:	2	2	1
• smooth and edit			
• generate toolpath			
Machining setup	1	1	1
Machining	2	2	1.5
Total	7	12	6.5

Table 1. Scanning and machining times for the bottom, side and top surfaces

After machining, some of the dimensions of the duplicated and original were measured manually at WR-ALC using a dial caliper. The comparisons are shown in the Table 2. The locations at which these measurements were made are shown in Figure 4.

Surface	Dimension Measured	Duplicated (in inches)	Original (in inches)	Error (in inches)
Bottom	Dim. 1 (width)	2.003	1.997	+0.006
Bottom	Dim. 2 (width)	3.259	3.251	+0.008
Bottom	Dim. 3 (width)	5.111	5.118	-0.007
Side	Dim. 4 (wall thick.)	.222	.235	-0.013
Side	Dim. 5 (wall thick.)	.139	.147	-0.008
Side	Dim. 6 (wall thick.)	.115	.132	-0.017
Side	Dim. 7 (wall thick.)	.135	.129	+0.006
Side	Dim. 8 (height)	.894	.891	+0.003
Side	Dim. 9 (height)	.899	.903	-0.004
Top	Dim. 10 (height)	.0509	0.510	-0.001
Top	Dim. 11 (height)	2.775	2.875	-0.010

Table 2. Measured dimensions for the duplicated and original leading-edge rib

The preliminary results show that the re-manufacturing approach is capable of reproducing complex geometric features. However, some of the part dimensions (Dim. 4 and Dim. 5) are out of tolerance, as seen in Table 2. Also, the quality of some portions of the machined surfaces were not acceptable.

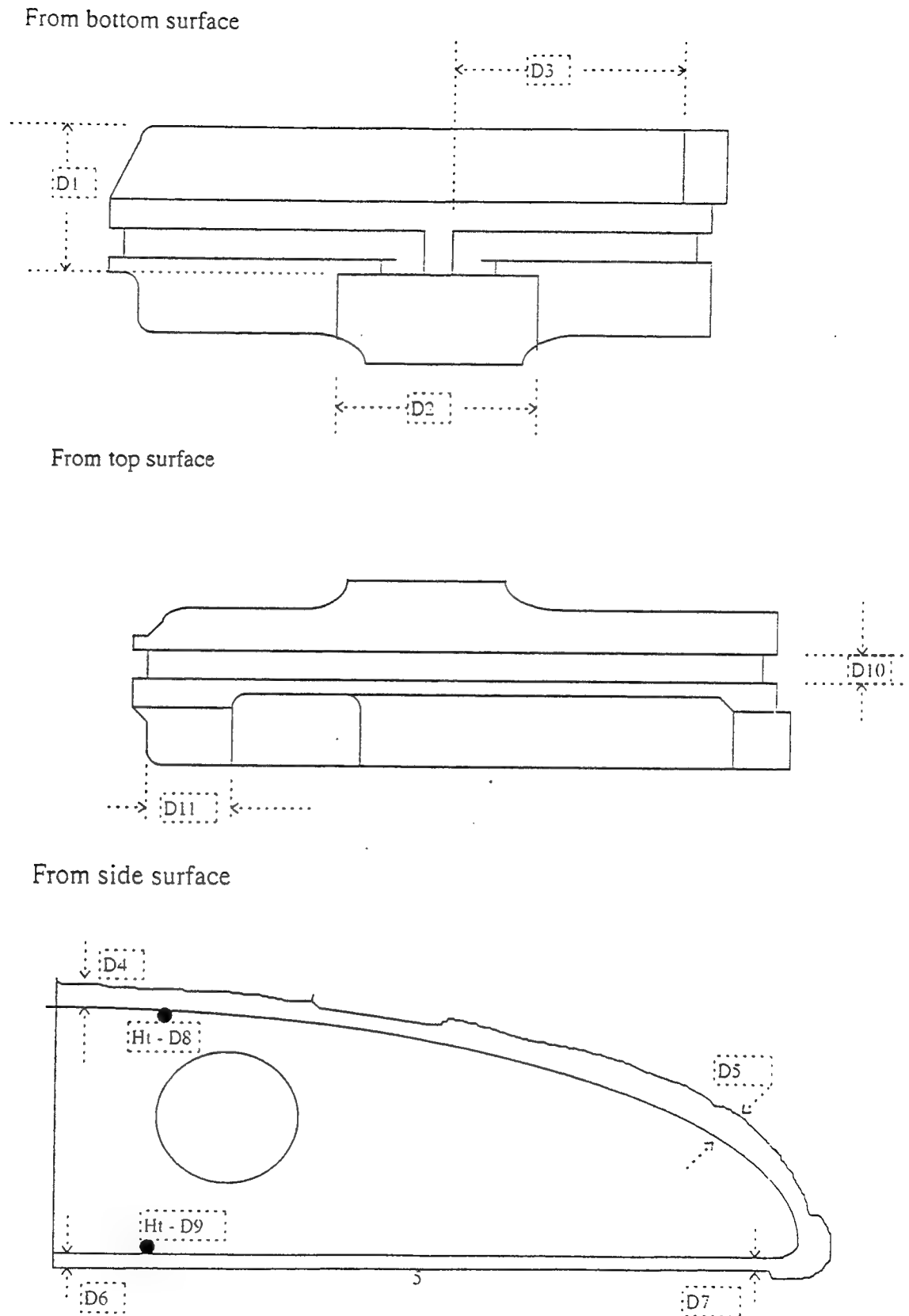


Figure 4. The approximate Locations Where the Measurements were Made

Discussion

Comparison of the exact CAD model of the leading edge rib and surface model reconstructed from the scanned point cloud data by LDI indicates that laser scanning offers a feasible solution for re-engineering aircraft structural components. Based on the results obtained for the test part, it is estimated that the modeling time is reduced by 20-30%. Since the modeler begins with point cloud data which contains all the geometric features of the part, the skill level required to construct the model is significantly lesser than that required for manual model creation.

There are three sources of errors for a part machined from a reconstructed CAD model: scanning, modeling, and machining errors. The errors in the reconstructed model by LDI comprises of the first two types of error: scanning and modeling errors. Since the maximum errors obtained are on the order of 0.005" and the machining error can usually be kept below 0.005", aircraft structural parts with tolerances of the order of 0.010" can, therefore, be manufactured using the re-engineering approach.

LDI is also capable of generating toolpaths directly from the scan data. An effort was initiated to compare the toolpaths generated from the surface model and those directly from the scan data. The quote for machining leading edge ribs using the toolpaths generated from these two different methods was too high (approximately \$20,000). Hence, this effort was not carried through. However, LDI engineers suggested that there is very little difference between the toolpaths generated by these two approaches. They claimed that the only difference is that there may be some surface bumps (on the order of 0.001") on surfaces machined by the toolpaths generated directly from the scan data. For aircraft structural components, this difference is not significant and can be ignored.

The scanning of the leading edge rib and machining of three of its surfaces at Sharnoa Corp. indicated that the re-manufacturing approach is a very promising method for reducing turnaround time at WR-ALC. In fact, since the model creation step is eliminated, the time savings realized are

much more than that for the re-engineering approach. By eliminating the model creation completely, the skill level for re-manufacturing has also been greatly reduced.

During scanning, the Sharnoa laser probe maintains a constant distance (approx. 6.25") between itself and the object being scanned. When it encounters geometric features such as vertical walls, the normally round laser beam becomes elliptical, resulting in a dramatic increase in the time taken to digitize the wall. Therefore, for surfaces surrounded by or containing deep pockets and vertical walls, it may be more efficient to digitize the surface with a mechanical probe and then generate toolpaths from the CAD model created specifically for that surface.

One of the difficulties encountered by Sharnoa Corp. while machining the wax part was the lack of adequate fixture to hold the part during scanning and machining. To reproduce a part accurately, good fixtures are required for both scanning and machining. This would very likely eliminate setup errors and reduce the machining time, which has been considered as the primary reason for the errors in the machined wax part.

A comparison of LDI's and Sharnoa's laser scanning systems brings to light the following characteristics of both systems. The Sharnoa laser software is designed specifically for part duplication and, therefore, it has less editing capabilities. Since Sharnoa is primarily a vendor of machining centers, the laser scanning is designed as an add-on feature to their machining centers, both scanning and machining can then be performed on the same machine. LDI, on the other hand, is a vendor of laser scanning systems, which have been designed for that sole purpose. Thus, their software is more versatile, but machining cannot be performed on their laser scanning equipment.

This machining test performed at Sharnoa Corp. demonstrated that the re-manufacturing approach using laser scanning was very promising, but not conclusive. To ensure that re-manufacturing can be successfully used to produce production parts at WR-ALC, further evaluation was deemed necessary. A contract was, therefore, awarded to Sharnoa in August, 95 to completely scan and machine two production parts: leading edge rib and canopy latch out of

the aluminum at Sharnoa. The canopy latch is a very complex part with a number of sculptured surfaces and a great deal of surface detail. At the time of this writing, the machining of this two parts has not been completed. The results will be presented in a follow-up report.

Conclusions and Recommendations

This feasibility study demonstrates the maturity of state-of-the-art laser scanning systems and they can be used to effectively reduce the turnaround time for the re-manufacture of aircraft structural parts with complex volumetric features. It was also found that X-Ray CT scanners are much more costly than laser scanners, requiring special facilities and high maintenance costs. If parts with internal features need to be re-manufactured, it would be more beneficial for WR-ALC to sub-contract X-Ray scanning of those parts than to acquire this technology.

Comparison of LDI's reconstructed model with the manually created surface model of the leading edge rib indicates that aircraft structural components can be re-engineered within tolerances. Evaluation of the partly machined wax test part shows that Sharnoa's laser scanning system is very promising for re-manufacturing applications. Additional tests are being conducted to validate this approach.

WR-ALC require both re-manufacturing and re-engineering approaches to manufacture aircraft structural components. If an accurate sample part is available, the re-manufacturing approach can be used. In case where design modifications are necessary or if the sample part has dimensional inaccuracy, the re-engineering approach provides a solution. The 3-D CAD model created during the re-engineering also facilitates subsequent operations, such as fixture design and part inspection. Since both technologies require an accurate and reliable laser scanner technology, the follow steps should be taken to acquire a scanner from one of the two vendors investigated in this study.

- Dimensional verification using CMM should be carried out for the two parts re-manufactured by Sharnoa Corp. If the leading edge rib is within tolerances and the surface finish is

acceptable, this would strongly indicate that the Sharnoa system would satisfy WR-ALC's manufacturing needs. For the canopy latch, lack of adequate fixturing is expected to adversely affect part accuracy. If the canopy latch does not satisfy tolerance requirements, errors could be due to scanning, machining, or both. For the latter case, the errors cannot be separated. Therefore, the only way to evaluate the Sharnoa laser would be to check if all the geometric features have been duplicated on the re-manufactured canopy latch. If all the geometric features are present, it would further prove that the Sharnoa scanner can be used to reproduce very complex parts. The errors caused by fixturing can be minimized at WR-ALC by properly fixturing the part during scanning and machining.

- To further evaluate LDI laser scanner capability, a canopy latch can be sent to LDI for surface model creation. The result would highlight the capabilities and limitations of their scanning technology, in the case of very complex parts. To evaluate the re-manufacturing capabilities of their software, a request can be made to generate toolpaths directly from their scan data for the leading edge rib and the canopy latch. The accuracy of the toolpaths can be evaluated at WR-ALC by actually conducting machining tests or using the NC-CUT software to simulate the cutting operations electronically.

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Electric Machines for Adjustable-Speed Drives

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ELECTRIC MACHINES FOR ADJUSTABLE-SPEED DRIVES

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Abstract

This summary compares the various types of electric machines used in high-performance variable-speed drive systems. The machines considered include: (i) brush dc, (ii) ac induction, (iii) synchronous and switched permanent magnet, and (iv) synchronous and switched reluctance motors. The focus of comparison will be placed on energy efficiency and servo control response (i.e., position and/or speed).

1. Introduction

Historically motor drives for industrial processes, commercial equipment, and domestic appliances have been designed to operate at constant speed. This was due to the ready availability of induction motors which could directly operate off constant frequency ac power supplies. It has been long recognized, however, that variable-speed drives offer improved performance and energy efficiency compared to their constant-speed counterparts. Until recently, the realization of continuously variable-speed drives has proven too expensive for all but a few applications (e.g., elevators, machine tools, and mill drives).

Electric drives are experiencing a revolution as a result of two main factors: (i) advances in power-electronics and microprocessor-based controls which facilitate the ready availability of low-cost, variable-frequency power supplies, and (ii) increased concerns over energy conservation and environmental issues. This brief examines variable-speed drive systems from the perspective of the electric motors used and the resulting drive performance which can be anticipated.

1.1. Drive Criteria

For a given application, the mechanical system to be driven (i.e., the load) will have specific criteria for torque and speed (i.e., a desired motion profile). The base torque T_b is normally the maximum continuous torque which must be supplied up to the continuous, or base, speed ω_b . As shown in Figure 1, servo drives typically operate in a constant torque mode from zero to rated speed, and in a constant power mode from rated to maximum speed.

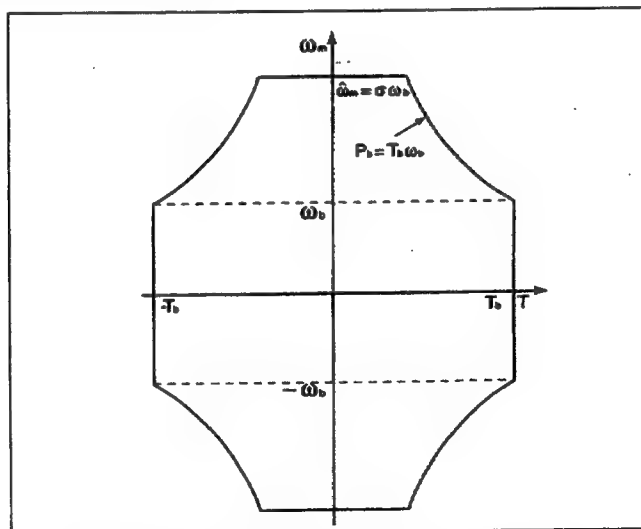


Figure 1: Typical region of drive operation.

In the constant torque region, the air-gap flux in the machine is held constant, whereas in the constant power region, the air-gap flux in the machine is weakened (e.g., by applying a stator flux in opposition to the rotor flux). This is mode of operation is known as field weakening or armature reaction. For many drive systems, operation is limited to the first or forward-drive quadrant (i.e., motoring); some applications, however, require reversed speed and regeneration capabilities (e.g., traction drives for electric vehicles).

For traction drives, the amount of power available from the electrical supply is often limited to the product $P_b = T_b \omega_b$. For these applications, rapid acceleration at low speed and operation at speeds above base speed is also desired (i.e., constant power up to a maximum speed $\hat{\omega} = \alpha \omega_b$). The constant power ratio α is typically in the range of 2 to 3, but can be as high as 6 for locomotive drives.

For high-performance drive systems which need to provide rapid acceleration/deceleration in either direction of rotation up to the base speed ω_b , a maximum transient torque \hat{T} is also specified. This maximum torque may be several times the allowable continuous base torque T_b . In addition, the time relation between the applied motor voltages/currents and the resultant motor torque is typically expressed in terms of a desired time constant or control bandwidth.

Servo drives are often designed to provide maximum torque per unit current out of the motor. This is done by minimizing the input current for a given torque. As a result, motor, inverter, and rectifier losses are minimized, which translates into higher drive efficiency and reduced system cost (i.e., due to the lower required ratings on the individual system components).

Other well known motor selection criteria which may be defined are: torque-to-rotor inertia ratio (e.g., for high-performance servo systems), energy efficiency (e.g., for electric vehicles), power-to-mass ratio (e.g., for airborne systems), torque ripple, acoustic noise, shape, volume, acceptability for hazardous environments, reliability, manufacturability, fail-safe features, initial cost, and present value of the total lifetime cost including the cost of energy.

2. Brush DC Motors

Brush dc motors (also known as commutator motors) have been widely-used for variable-speed drive applications. A cross section of a typical brush dc machine is shown below in Figure 2. Around the stator structure, a number of iron poles project inward from a cylindrical iron yoke. Current in field coils encircling each of the stator poles produces magnetic flux in the air-gap between the poles and a central armature (i.e., the motor rotor). This flux path returns through the adjacent stator poles. The motor armature is typically made of iron laminations and has axially directed slots in its outer surface. These slots accommodate current carrying conductors. The coils of the armature winding are connected to a commutator, or segmented mechanical switch, which is mounted on the rotor. The commutator continuously switches the armature conductors via mechanical brushes such that the conductors under each pole carry similarly directed currents.

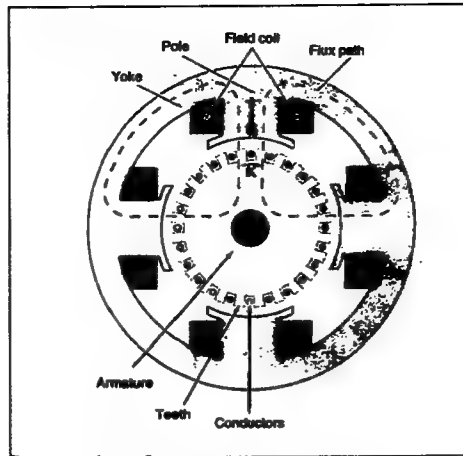


Figure 2: DC brush motor.

2.1. Torque Production

The interaction of the axially directed armature currents and the radially directed magnetic flux produces torque on the motor shaft. The torque may be expressed as

$$T = 2\pi r^2 l \gamma B K,$$

where r is the rotor radius, l is the axial rotor length, and γ is the fraction of the rotor surface covered by the poles, B is the radial flux density in the air-gap, and K is the current density around the armature surface. Note, regeneration is achieved by reversing the armature current direction while speed reversal is obtained by reversing the armature (i.e., supply) voltage.

2.2. Design Considerations

The continuous value of the current density K is limited mainly by the maximum acceptable temperature of the armature winding insulation. The loss power which can be conducted away by cooling air depends mainly on the air velocity and is typically in the range of 20 to 100 W/m² of surface area for each degree Celsius of temperature difference between the surface and the cooling air. Using these concepts, a first approximation for the rotor dimensions can often be obtained.

2.3. Efficiency

Armature losses are significant in the brush dc motor, and vary from 60% of the total losses for small machines to 35% for large machines. In addition to armature losses, the brush dc motor has losses in the iron laminations of the rotor core, conductor losses in the field windings, losses due to the voltage drop across the commutator (e.g., approximately 2V), losses due to friction in the bearings and commutator, and loss due to windage. Typical values for the efficiency of a fully loaded 5 to 150kW motor is in the range of 83 to 93%.

2.4. Operational Considerations

For constant power operation, the number of turns on the armature windings and their series-parallel connections through the commutator are designed such that the voltage generated by the armature is approximately equal to the maximum supply voltage V_b at the base speed ω_b and maximum field flux. The flux density in the air-gap is adjusted by controlling the current in the stator field windings. Normally for all speeds below ω_b , this flux is kept constant at its maximum value so that the maximum torque per amp of armature current and, thus, minimum winding loss is achieved. To operate the motor at its constant power limit at speeds above ω_b , the field current is controlled such that the flux density is reduced inversely proportional to the speed. This keeps the generated armature voltage constant at V_b and the armature current at its rated value.

2.5. Limitations

For high-performance applications, the maximum torque produced is limited by the current that the commutator can switch without excessive sparking (i.e., typically 2 to 5 times the continuous rated current). While brush dc motors have very desirable control characteristics, their use is limited by a number of factors: (i) the need for regular commutator maintenance (e.g., brush replacement), (ii) the relatively heavy rotor with high inertia, (iii) difficulty in producing a totally enclosed motor for some hazardous applications, (iv) a limit on the constant power speed range due to commutation difficulties at low values of flux, (v) a relatively low maximum rotor speed limited by mechanical stress on the commutator, and (vi) relatively high cost.

3. AC Induction Motors

A cross section of a two-pole induction motor is shown below in Figure 3. Slots in the inner periphery of the stator accommodate three phase windings a , b , and c . The turns in each winding are distributed so that a current in one winding produces a sinusoidally distributed flux density around the periphery of the air-gap. When three currents which are sinusoidally varying with respect to time flow through the three symmetrically placed windings, a flux density is produced which is sinusoidally distributed around the air-gap. This air-gap flux density rotates at an electrical angular velocity equal to the angular frequency of the stator currents ω_s (i.e., so-called synchronous speed).

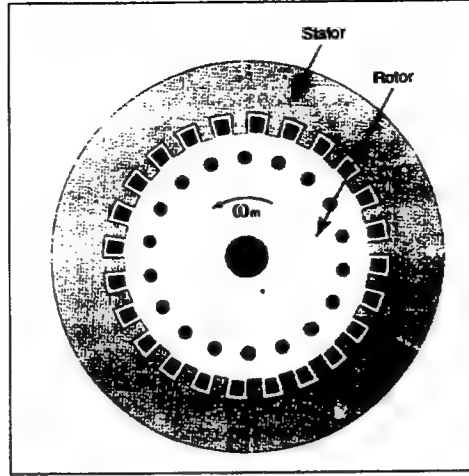


Figure 3: AC induction motor.

The most common type of induction motor has a squirrel cage rotor in which aluminum conductors or bars are cast into slots on the outer periphery of the rotor. These conductors are shorted together at both ends of the rotor by cast aluminum end rings, which are often shaped to act as fans for cooling the rotor. In larger machines, copper or copper-alloy bars are used to fabricate the rotor cage windings (to reduce losses).

As the sinusoidally distributed flux density waveform sweeps past the shorted rotor conductors, it generates a voltage across the rotor bars. This induced rotor voltage produces a sinusoidally distributed set of rotor currents. The angular frequency of the induced rotor currents ω_r is equal to the difference between the angular frequency of the stator currents ω_s and the angular rotor velocity (i.e., the mechanical speed of the machine), ω_m , as shown

$$\omega_r = \omega_s - \omega_m.$$

The range of the rotor frequency at rated load (i.e., $\frac{\omega_r}{2\pi}$), varies from about 5Hz for small machines to 0.5Hz for very large machines.

3.1. Torque Production

The torque produced by an induction motor is equal to the power crossing the air-gap divided by the mechanical rotor velocity ω_m . For small values of ω_r , the rms value of the current density in the motor rotor K_r is nearly proportional to ω_r and is in phase with the sinusoidally distributed air-gap flux density of rms value B_g . This interaction produces a torque on the rotor of the form

$$T = 2\pi r^2 l B_g K_r,$$

where r is the rotor radius and l is the axial rotor length.

Note, for motoring action ω_r is positive. To produce regeneration with reversed torque the load must drive the angular rotor velocity to a value greater than the stator angular frequency, making ω_r negative (i.e., this implies that the sequence of the rotor currents is reversed). Similarly, to reverse the motor's direction of rotation, the sequence of stator currents must be reversed (i.e., from *abc* to *acb*).

The induction motor dynamics are often described in terms of motor slip. Slip is simply the normalized difference between the electrical angular velocity of the stator currents and the electrical angular velocity of the rotor currents, defined as shown

$$s = \frac{\omega_s - \omega_m}{\omega_s} = \frac{\omega_r}{\omega_s}.$$

Given this, torque is positive when the slip is positive (i.e., motoring action), negative when the slip is negative (i.e., generator action), and zero when the slip is zero (i.e., operating at synchronous speed).

3.2. Design Considerations

While two-pole induction motors are used in some variable-speed drives, four or more poles are more common. In a p -pole motor, the sinusoidal distribution of each phase winding is repeated for $p/2$ complete waveforms around the stator. The angular rotor velocity at synchronous speed (i.e., zero torque and slip), is given by

$$\omega_m = \frac{2}{p} \omega_s.$$

The optimum induction motor design for variable-speed drive systems in the low to medium-power range typically has 2 or 4 poles, with higher pole numbers commonly found in high-power low-speed applications. The torque capability of the machine does not necessarily change with an increase in the number of motor poles.

From a structural standpoint, however, for a given frame size an increase in the number of poles facilitates a larger rotor radius. Since the base torque is proportional to the rotor radius, the power rating obtainable from a given frame size can be increased by increasing the number of motor poles. Other consequences of increasing the number of motor poles include: (i) a decrease in power factor, (ii) an increase in motor losses (i.e., both stator and stray), (iii) an increase in the required power supply rating, and (iv) an increase in the required frequency of the supply (i.e., in proportion to the number of poles).

The primary factor in establishing an induction motor's base torque is the continuous rating of current density in the rotor and stator. These ratings are determined by heat dissipation considerations as noted above for the brush dc motor. Induction motors designed for variable-frequency operation (e.g., under vector control), have as low a rotor resistance as possible in order to minimize losses (e.g., class A and B motors are preferred).

3.3. Efficiency

In the past, induction motors (especially those in appliances), were designed to achieve minimal initial cost. Today energy conservation and environmental impact are major

concerns. Machine efficiency has, therefore, become an important design consideration. The power losses in the stator and rotor windings can be determined using a simple equivalent circuit model of the induction motor. At rated load, these losses can each account for 25-30% of the total loss. In addition, there are core/yoke losses which account for 15-20% of the total. Losses due to high-frequency local oscillations in stator/rotor poles around the air-gap (i.e., stray losses), typically account for 10-15% of the total. Finally, there are friction and windage losses which account for 5-10% of the total.

Recently, emphasis has been placed on the design of high-efficiency induction motors. These motors use more conductor material in both the stator and rotor to achieve lower winding resistance losses. These machines also use a higher quality iron with lower flux density in the stator to reduce core losses. The air-gap length is also increased to reduce stray losses. For a given rating, high-efficiency motors have the same frame size as a standard induction motor but are longer axially.

The initial cost of a high-efficiency motor is up to 25% more. Typical efficiencies for standard and high-efficiency, 4-pole, 60Hz, induction motors are: 84 and 90% at 10kW, 92 and 94% at 100kW, and 93 and 96% at 1000kW, respectively.

3.4. Operational Considerations

The continuous torque rating of an induction motor T_b is typically 40-50% of the maximum torque \hat{T} . Constant power can be achieved up to the maximum rated speed $\hat{\omega}$, at which point the peak available torque is less than the base torque (i.e., a constant power ratio of $\alpha = 2 - 2.5$ is typically possible). It is often not possible to operate the induction motor continuously over the entire constant power range, because at limiting speeds the power factor starts to decrease (e.g., to as low as 0.7). This can cause a corresponding increase in the stator currents beyond their rated value, resulting in excessive motor heating (i.e., unless the duty cycle is low).

For variable-speed applications, the voltage source is typically an inverter which uses solid-state switches to produce approximately sinusoidal voltages of controllable magnitude and frequency. Most inverters use pulse width modulation (PWM) schemes to produce voltage waveforms having negligible low order harmonics. These waveforms consist of pulses formed by switching between the positive and negative sides of a dc link, at a relatively high frequency (e.g., typically greater than 15kHz).

Induction motors are commonly used in high-performance applications requiring rapid and precise motion control. Under these circumstances, an approach called vector control is often used. The technique requires some means of continuously measuring and/or estimating the rotor flux and position (note, such measurements are not always readily available). Using vector control, the motor is capable of accurately generating desired torque profiles to the extent that the inverter can supply instantaneous current. This feature combined with the relatively low inertia of the induction motor rotor, makes the machine an attractive choice for servo-control applications (e.g., induction motors are frequently used in traction applications such as locomotives or road vehicles).

Most vector control applications require little or no motor derating. If the motor is

cooled solely by its internal rotor fan, however, it may have to be derated for low-speed operation. Typically for constant torque applications, an 80% rating is acceptable for 20% rated speed (as low as 50% at very low speeds). This derating may be avoided if auxiliary cooling is used (e.g., forced air or oil).

The rugged construction of the induction motor allows for relatively high values of maximum speed, limited by the bearing life, windage losses, and the natural (i.e., critical) frequency of the rotor. Induction machines have been successfully operated in the 5,000-50,000 RPM range.

3.5. Advantages

Induction motors are simpler in structure than dc brush motors and, as a result, their initial cost is substantially less. The efficiency of the two machines, however, is comparable. In addition, the induction motor is: (i) more robust and reliable than the brush dc motor, (ii) can be designed to operate in dirty and explosive environments, and (iii) requires little maintenance. All of these features make the induction motor an attractive choice for industrial and commercial drive systems.

The use of high-efficiency, rather than standard induction motors, adds somewhat to the initial cost of the drive system. This cost is more than offset, however, by the increase in efficiency and reduction in cost of operation. For example, a typical increase in efficiency of 6% is obtained for a 10kW high-efficiency motor versus standard designs. If this motor is operated near rated load 80% of the time, the savings will be 4,200kWh per year or \$250 (assuming electric energy costs are 6c/kWh). This type of high-efficiency machine typically cost \$150 more than standard designs. Thus, the added initial investment can be recovered within 8 months of operation. Alternatively, the present value of energy saved over a 15-year lifetime (assuming 6% interest), is about \$2,450 (i.e., 16 times the initial difference in cost).

4. PM Motors

Permanent magnet (PM) motors use magnets to produce the air-gap magnetic field rather than using field coils (as in the dc brush motor) or requiring a magnetizing component of stator current (as in the induction motor). Significant advantages arise from the resulting reduction in losses and the corresponding improvement in energy efficiency. The two most common types of PM motors are synchronous (i.e., with a uniformly rotating stator field, as in an induction motor) and switched (i.e., with a stator field which is switched in discrete steps). The construction of the two PM motors is very similar. A representative PM motor is shown below in Figure 4.

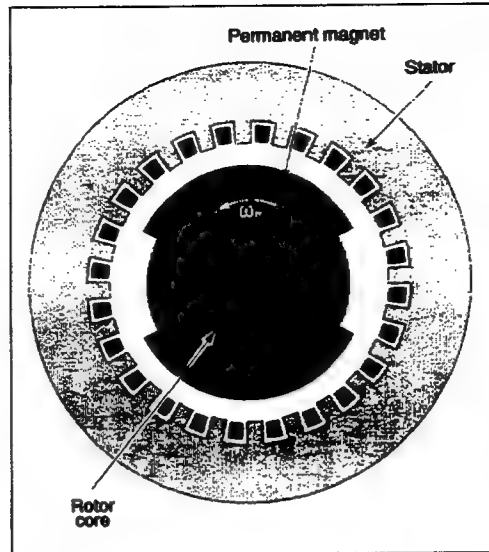


Figure 4: Permanent magnet brushless dc motor.

The rotor has an iron core which may be solid or made of punched laminations. Thin permanent magnets are typically mounted on the surface of this core using epoxy adhesives. Alternating magnets of opposite magnetizing direction produce a radially directed flux density across the air-gap. This flux density reacts with winding currents placed in slots on the inner surface of the stator to produce torque. PM motors are normally constructed with totally enclosed rotors.

4.1. PM Synchronous

The typical PM synchronous motor (PMSM) has a rotor magnet coverage of approximately two thirds. The stator is essentially identical to that of an induction motor. The three-phase windings are distributed to provide a near-sinusoidal distribution of current density around the air-gap periphery. Given this, a set of sinusoidally distributed phase currents produces a sinusoidally distributed flux around the air-gap. The flux density rotates at an electrical angular velocity of ω_s and, for a p -pole motor, generates a mechanical (i.e., rotor) angular velocity of

$$\omega_m = \frac{2}{p} \omega_s.$$

The electrical effect of this rotor rotation can be modeled as a sinusoidal current source with an angular frequency of $\omega_s - \frac{p}{2} \omega_m$. This current can be represented as a phasor $I_f \angle 0$. The corresponding stator current phasor is then given by $I_s \angle \beta$, where β is the electrical phase angle between the peak stator current density and the magnetic flux axis. As such, β is a function of the angular position of the motor rotor. Note, I_f typically has a maximum magnitude of 2-5 times the rated stator current.

4.1.1. Torque Production

A PMSM provides continuous torque only when the rotor speed is directly related to the power supply frequency. The supply may be either voltage or current controlled source. The stator voltages or currents are then constructed (i.e., via switching action of the inverter) to produce a desired relative instantaneous angle β . For a current-source drive, the motor torque can be derived as the air-gap power divided by the mechanical angular velocity, and expressed as

$$T = \frac{3p}{2} L_m I_f I_s \sin(\beta),$$

where L_m is the motor's magnetizing inductance. Note, maximum motor torque is obtained by operating with $\beta = 90^\circ$. This condition is practical up to a speed at which the voltage limit of the inverter is reached. Above this speed, a more appropriate operating condition is one which provides unity power factor by increasing the lead angle β and maximizes the utilization of the inverter volt-amp rating with only a small reduction in torque output. For regeneration, the rotor angle β is made similarly negative. Note, PMSM drives require a continuous rotor position sensor (i.e., an absolute encoder) for control purposes.

4.2. PM Switched

The PM switched motor owes its origin to an attempt to invert the brush dc motor, to remove the need for the commutator and brush gear. The commutator in the brush dc motor converts the input dc current into approximately rectangular shaped currents of variable frequency. By applying this rectangular-shaped current directly to the stator of the motor and transferring the field excitation to the rotor (in the form of a permanent magnet), an inversion of the brush dc machine is achieved — with the advantage that the new machine does not have a mechanical commutator and brush gear. Given this, the PM switched motor is often referred to as a brushless dc motor (BDCM) or trapezoidally excited motor.

The BDCM is, in most respects, identical to the PMSM. The stator windings are similar to those of the PMSM except that the conductors of each phase winding are distributed uniformly in slots over two arcs of 60° . The electrical power supply is designed to provide near rectangular pulses of current which are sequentially switched to the three stator terminals. The sequence of switching actions is triggered by signals from a position sensor(s) (e.g., an encoder or Hall-effect devices), mounted on the motor shaft. Six steps of this switching cycle are required per revolution for a two-pole motor.

4.2.1. Torque Production

Each stator phase winding of the BDCM carries the supply current for two-thirds of the time; therefore, the torque produced by the motor can be approximated as

$$T = \sqrt{\frac{2}{3}} 2\pi r^2 l B_g K_s,$$

where B_g is the air-gap flux density and K_s is the rms value of the current density in the winding. The motor behaves very much like a dc brush motor. Its speed is approximately proportional to the applied direct voltage. Its ripple torque can be made relatively small, but tends to be larger than that of a well-designed synchronous PM motor. There is little difference between the efficiencies of the synchronous and switched PM machines.

4.3. Design Considerations

For both PM motors, the magnets are bonded to the rotor core using epoxy adhesives. These adhesives must have good aging properties and a wide temperature range. The maximum speed of the rotor is limited by the action of the centrifugal force on the adhesive, proportional to $r\omega_m^2$. For larger, high-speed motors it may be desirable to band to rotor with glass or carbon fiber tape under tension. Theoretically, there appears to be no inherent limit on the maximum rating of torque or power for PM motors. Both types of PM motor are capable of very fast dynamic responses, limited mainly by the supply inverter. This rapid response can be achieved using controllers which are much simpler than the vector controllers commonly used for induction motors.

4.4. Operational Considerations

Demagnetization of the rotor magnets can occur if the flux density is reduced to less than the so-called "knee-point" density (as determined by the material's B-H characteristics). This can result in permanent reduction of torque capability since it is usually not feasible to remagnetize the magnets without disassembling the motor. Most PM motors are designed to withstand considerable overload currents without danger to the magnets. For example in a PMSM, the stator current I_s can usually exceed the magnetizing current (i.e., 2-5 times over rated), without demagnetization.

The primary danger to the magnets arises from a short circuit on the stator following a failure in the inverter. In a PMSM, the resulting short-circuit current has a steady-state component which is equal to the equivalent magnet current I_f with an initial transient component of equal magnitude. This transient component can damage larger motors, which typically have large electrical time constants in comparison to the excitation period.

4.5. Efficiency

The PM motors are, potentially, much more efficient than induction motors, since the electrical losses occur only in the stator core and windings (i.e., negligible rotor losses). Comparing PM and induction motors of the same size and shape: friction losses will be similar while windage losses will be less for the PM motor (since it does not require an internal fan for rotor cooling). The core losses in a surface-mounted PM motor will typically be 1.4-2 times greater than in a similar induction motor. The PM motor can, however, be operated at unity power factor — while the induction motor will always have a lagging power factor (typically in the range of 0.8-0.9 for

four pole motors, and lower for $p > 4$). Furthermore, the overall drive efficiency for the PM motor is improved because the rating (and therefore losses) in the inverter is reduced roughly in proportion to the power factor.

For similarly rated machines, the total losses in the PM motor will typically be about 50-60% of those in the induction motor. Efficiency for PM motors in the 10-100KW range is 95-97%. Furthermore, PM motors are up to 40% more efficient than induction motors during low speed operation (i.e., less than rated). Another benefit of the PM motor is that the number of poles can be selected to optimize motor efficiency (e.g., the optimum number of poles is frequently in the range of 8-12). In addition, increasing the number of poles allows the same amount of torque to be produced by a shorter machine.

4.6. Advantages

The surface PM motor has the potential to replace the induction motor in a wide variety of industrial, commercial, and domestic variable-speed drive applications based on its superior efficiency. The original cost of a PM motor is higher than a comparable induction motor, mainly due to the cost of its magnets; however, the present value of energy saved by a 1% increase in efficiency is about \$50/kW of motor rating (assuming electric energy costs of \$0.06/kWh, operation at continuous rated load, 6% interest, and a 15 year lifetime). Thus, the potential 3-7% efficiency increase achieved by PM motors in the 1-100KW range translates into \$150 to \$350 per kW of rating. This is many times the original trade cost of induction motors, and well above the estimated production cost of PM motors.

In traction applications, the surface PM motor may be a good choice even without the use of flux weakening. For these applications, the motor size is determined by the required base torque. The stator windings are designed so that the generated voltage is equal to the supply voltage at maximum speed (rather than at base speed). For operation above the base speed in the constant-power range, the stator current from the inverter is reduced inversely to the speed. This mode of high-speed operation reduces the stator winding losses compared to a machine in which flux weakening is used. For electric road vehicles, which must carry their power supply, the energy savings which result from this approach may be sufficient to overcome the additional cost of the larger inverter required. Another advantage: if the dc supply to the inverter is lost, the open-circuit voltage applied to the inverter switches will be within their normal ratings.

When the major interest is in obtaining maximum acceleration from the motor (e.g., robotics and machine tools), surface PM motors using NdFeB magnets work particularly well. The PM motor has an additional advantage in that its mass and volume can be considerably less than either a dc brush or induction motor of similar maximum torque rating. As such, PM motors have a higher torque-to-inertia ratio than brush dc or induction motors.

4.6.1. PMSM Versus BDCM

Assuming equal copper losses, the BDCM is capable of 15% higher power density than the PMSM. The BDCM has a higher torque per unit peak current than the PMSM, assuming both are operating in constant torque mode. For this reason, the BDCM is often preferred when space/weight is a constraint (i.e., airborne systems). The ripple torque of a BDCM is inherently greater than that of a PMSM. The ripple torque in the PMSM is due to the ripple in the supplied currents. Since these currents ripples are typically of high frequency, they are easily damped out by the load inertia. The BDCM, however, also experiences a commutation ripple which is a function of the machine speed. Continuous rotor position feedback is needed by the PMSM for proper operation, whereas for speed control applications the BDCM only requires rotor feedback sensing every 60° . Note, both machines require continuous position feedback for position control applications. An inverter with a given continuous current and voltage rating could theoretically drive a BDCM of 33% higher power rating than a PMSM. The PMSM is capable of a higher speed range than a BDCM with the same parameters; therefore, the PMSM is preferred for applications where flux-weakening is required.

5. Reluctance Motors

A reluctance motor is one in which torque is produced by the tendency of its movable parts to move to a position where the inductance of the excited winding is maximized. Both rotary and linear reluctance motors are possible. Reluctance motors have no field windings or permanent magnets. Consequently their rotors are much simpler and less expensive to manufacture than other types of machines. As a result they are more suitable for high speed and/or high temperature environments. There are two main types of reluctance machines — synchronous and switched. Although the names sound similar, the two motors are radically different. One is a true synchronous ac motor, while the other is a special form of variable-reluctance stepper motor.

5.1. Synchronous Reluctance Motors

A simple two-pole synchronous reluctance (SYNR) motor is shown below in Figure 5. The stator is identical to that of an induction or PMSM motor. A sinusoidally distributed rotating flux density is produced in the air-gap by a three-phase set of sinusoidal stator winding currents. The rotor is shaped with a small air-gap in the direct (d) axis, and a large axis in the quadrature (q) axis. The rotor of the motor is made of iron laminations separated by nonmagnetic material to increase the reluctance to flux in the q-axis.

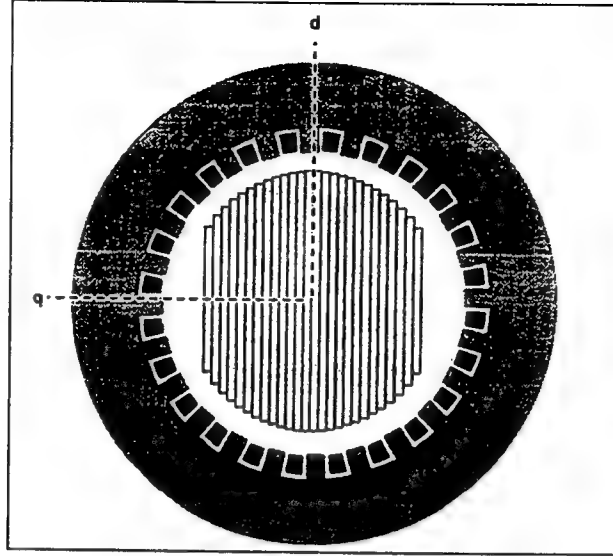


Figure 5: Synchronous reluctance motor.

5.1.1. Torque Production

When the rotor rotates synchronously (i.e., the peak of the flux density is aligned with the direct axis), the magnetic inductance is L_d ; when aligned with the quadrature axis it is L_q . The torque for the motor can be expressed as

$$T = -\frac{3p}{4} \left[1 - \frac{L_q}{L_d} \right] \frac{\Lambda_s^2}{L_q} \sin(2\delta),$$

where Λ_s^2 is the rms value of the stator flux linkage and δ is the angle by which the rotating stator current density leads the rotor direct axis (note, δ is dependent on the rotor position). This expression shows that the SYNRMotor can have a maximum torque similar to that of an induction motor, if the saliency ratio is high (i.e., $\frac{L_d}{L_q}$).

To the extent that this can be achieved, the performance of the SYNRMotor is remarkably like the induction motor (i.e., when designed for continuous operation at maximum power factor, rated torque is 0.5-0.6 of maximum torque). Note, the SYNRMotor can also be made with uniformly distributed windings and operated in a switched mode similar to the BDCM.

5.1.2. Design and Operational Considerations

The SYNRMotor can use induction or PM motor laminations for the stator. The rotor diameter is comparable to that of an induction motor. Motor excitation is via a set of polyphase sinewave currents or voltages. D,q-axis theory applies to the motor; this implies: (i) sinewave currents produce constant torque, (ii) it can be controlled by a field oriented ac controller (i.e., as with the induction motor, the "field" current can

be separated from the "armature" current using vector control), and (iii) there is at least one frame of reference in which the voltages, currents, and flux-linkages appear to be constant (dc). As such, the SYNRMotor can not operate from an uncontrolled ac power line and absolute position feedback is required for control purposes.

The power electronics circuit is identical to that used for PWM control of induction motors. Common parts with induction motors (assuming vector control), include: (i) the entire stator core and windings, (ii) the power electronic controller, except for possible software changes, and (iii) the rotor position sensor. The constant power speed capability is close to that of a comparable induction motor.

The SYNRMotor has a slightly higher energy efficiency compared to an energy-efficient induction motor at rated speed and is significantly better at low speeds (up to 40% more). The torque-to-inertia is comparable to that of an induction motor. The SYNRMotor is susceptible to cogging torque (as high as 15%), and as such, is not as quiet as a comparable PMSM motor. In addition, the SYNRMotor is not well suited to high speed operation due to the nature of its rotor construction.

The main strengths of the SYNRMotor include: (i) synchronous operation with vector control using standard ac stator and power electronic controller, (ii) wide constant-speed range ($\alpha > 7.5$), and (iii) higher low-speed torque than an induction motor (up to 40%), due to lower rotor losses. Its main weaknesses include: (i) to compete with induction motors requires an axially-laminated design which is expensive, (ii) performance is only marginally better than a standard energy-efficient induction motors (except at low speeds), (iii) unsuitable for very high speed applications due to rotor construction, and (iv) requires absolute shaft position feedback.

5.2. Switched Reluctance Motors

The switched reluctance (SR) motor has a doubly salient structure. A three phase, 6 stator pole and 4 rotor pole machine (known as a 6/4 motor), is illustrated below in Figure 6. Each stator pole is surrounded by a coil with the coils of two opposite poles being connected in either parallel or series, to form the three phase windings.

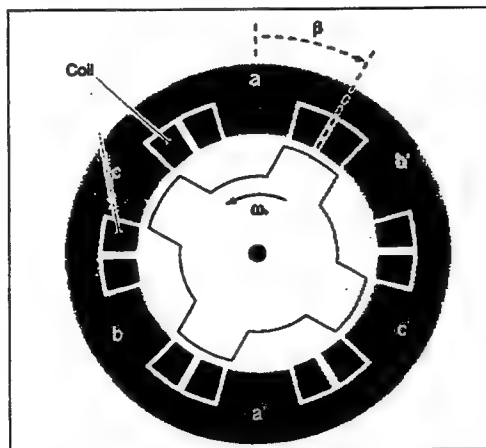


Figure 6: Switched reluctance motor.

If the supply current is switched through the coils of phase a , there will be a counterclockwise torque acting to align a pair of rotor poles with the phase a stator poles. When aligned, if the current is now switched to phase b , the counterclockwise torque will continue. As such, the rotor moves $\frac{\pi}{6}$ radians for each step. Thus, 12 switching operations are required per rotor revolution. Note, the direction of the coil current is irrelevant. The direction of rotation can be changed by reversing the sequence of the energized phase currents to acb .

Many variations in the choice of stator and rotor poles configurations are possible. For example, 8/6 (4 phase) and 10/8 (5 phase) motors have been used to create variable-speed drives. It is also possible to create machines with multiple redundant phases. Such configurations are particularly useful in aerospace power applications which must be highly fault tolerant (e.g., internal starter generators used in the development of More Electric Aircraft).

5.2.1. Torque Production

The SR motor is a complex machine with highly nonlinear dynamics. An approximate expression for the torque produced by an SR motor can, however, be expressed as

$$T = \frac{k}{\sqrt{3}} \pi r^2 l \hat{B} K_s,$$

where \hat{B} is the maximum air-gap flux density when the stator and rotor poles are aligned, K_s is the rms value of the stator current density, l is the axial rotor length, r is the rotor radius, and k is a saturation constant (from 0.45 to 0.75 for unsaturated to saturated machines, respectively). Note the similarity in the torque expressions for the SR motor and the BDCM.

5.2.2. Design and Operational Considerations

SR motor excitation consists of a sequence of properly timed voltage or current pulses applied to each phase (i.e., the motor can not operate from an uncontrolled ac power line). For good performance, the design of the switched reluctance motor must be closely coordinated with the design of its power converter and controller. This coordination is much more significant than for the induction or PM motor drives.

D,q-axis theory does not apply to the SR motor; this implies: (i) constant current does not produce constant torque, (ii) the controllers bear no relation to field-oriented controllers, (iii) there is no frame of reference in which the voltages, currents, and flux-linkages are constant. Unlike synchronous machines, the "field" current can not be separated from the "armature" current using vector control; therefore, torque control must be instantaneous (i.e., by shaping the current waveform profile). This profile is specific for each motor and varies with load and speed. The switched reluctance motor drive system has no electromagnetic or electronic components in common with the induction motor (i.e., the power electronics circuit is unique). Position feedback requirements for the SR motor are similar to those for the BDCM.

The constant power speed capability of the SR motor is close to that of a comparable induction motor. The torque-to-inertia ratio is, however, significantly higher (e.g., 2-5 times) than that of the induction motor — but not as high as a BDCM with rare earth magnets. Ripple torque is inherent to the SR motor. The amount of ripple torque can range from 100% at high speeds (e.g., for “single-pulse” mode of operation) to less than 1% at low-speed (e.g., using well-designed current profiling). As a result, the SR motor is typically noisier than a comparable PM motor.

The SR motor is well suited to high speed operation, but critical shaft speeds can be lower than comparable PM motors. Main SR motor strengths include: (i) simple construction, (ii) suitable for high speeds and high temperature operation, (iii) higher low-speed torque compared to an induction motor (up to 40%), and (iv) relatively free of dangerous failure modes. Main weaknesses: (i) no common components with other motor drives, (ii) tight manufacturing tolerances required to make a quiet motor, (iii) requires a high electric loading to compensate for low magnetic loading (i.e., requires more copper weight or higher temperature rises), (iv) controller is unique, difficult to design, and specific to each application, (v) torque ripple is inherent, and (vi) uniqueness of technology diminishes end-user confidence, especially in markets where established technologies can do the same job (e.g., ac induction and PM motors).

5.3. PM-Reluctance Motors

The permanent magnet (PM) reluctance motor is a form of synchronous reluctance motor which has magnets buried in the rotor, as shown below in Figure 7. It has many of the same characteristics associated with the SYNRMotor. The constant power speed capability is, however, greatly extended (i.e., α is in the range 2-5). Buried PM machines are capable of a higher torque per unit current than surface-mounted PM machines (up to 40% more). Buried PM machines are, however, more sensitive to parameter changes than surface-mounted PM machines. This puts a greater burden on the motor controller to achieve an accurate servo response.

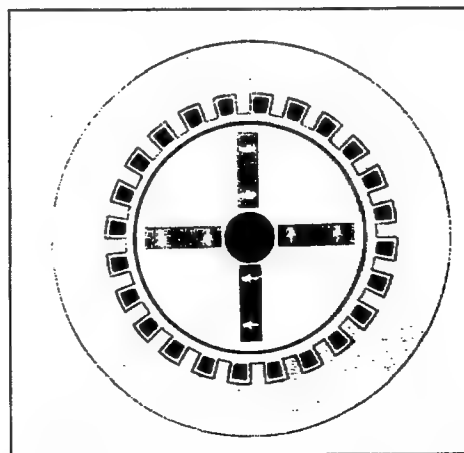


Figure 7: Permanent magnet reluctance motor.

6. Conclusions

The reasons for choosing brushless servo motors over brush type dc motors include: robustness, higher torque and speed bandwidths, and lower maintenance. The mechanical commutator and brushes of the dc motor also enforce severe limitations on its maximum speed and over current capabilities. Assuming that the decision has been made to use a brushless motor, the next decision to make is whether to use an ac or switched reluctance motor. The SR motor is, inherently, a pulsating torque machine; therefore, if a reasonably smooth torque output is desired, an ac motor is typically preferred (note, the SR motor also represents a relatively green technology). The next decision to be made is whether or not to choose an induction or PM motor (note, the SYNRM motor may also be considered, but it too is a green technology).

PM motor drives have the following advantages over induction motor drives: (i) higher torque to inertia ratio (i.e., faster response for a given electrical torque), (ii) higher efficiency and less heating problems due to negligible rotor losses, (iii) the induction motor requires a source of magnetizing current while excitation of the PM motor is via the rotor magnet (allows electronic braking during power supply failure), (iv) the induction motor requires a larger rated rectifier and inverter compare to a similarly rated PM motor due to lower efficiency and need for magnetizing current, and (v) the PM machine is smaller in size/weight (i.e., higher power density) than an induction motor of the same capacity. Induction motor drives have the following advantages over PM motor drives: (i) larger field weakening range of operation and ease of control in this mode of operation, (ii) lower cogging torques, (iii) lower cost, and (iv) can operate at higher temperatures.

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**A GC-MS Study of Quantitative Determinations of Amphetamines
and Methamphetamines and the Removal [By Periodate Oxidation]
of Possible Interference by Ephedrine**

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A GC-MS STUDY OF QUANTITATIVE DETERMINATIONS
OF AMPHETAMINES AND METHAMPHETAMINES AND
THE REMOVAL [BY PERIODATE OXIDATION] OF
POSSIBLE INTERFERENCE BY EPHEDRINE

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ABSTRACT

In the GC-MS determination of the following drugs of abuse (DA), amphetamine (AM) and methamphetamine (MAP), ephedrine (EP) is known to interfere, in particular because of the sometimes excessive concentrations of the latter compound [which is an Over-the-Counter (OTC) item] found in urine and blood samples. Earlier work by Buddha Paul et al. has suggested that the EP (and pseudo-ephedrine and propanolamine) may be removed by periodate oxidation. The present study was undertaken to test this suggestion and delineate more specifically the optimal conditions for this process.

INTRODUCTION

Screening for illegal drugs in the work-place is a critical, large scale (and expensive) activity of great importance to Federal and State Governments, the Armed Forces, Industry and private businesses alike. The success of drug screening programs may spell the difference between acceptable public safety risks and disastrous accidents or drug related crimes - not to mention long-term medical costs for the treatment of drug abusers. Obviously, to be successful, a screening program must be of such scientific quality as to stand up to challenges in a Court of Law. One of the grounds for objections in a Court of Law is the possibility of false positive results caused by one or more legal compounds or drugs, whether prescribed by a physician or available as an Over-the-Counter preparation.

The study reported here was performed during the summer of 1995 at the Clinical Investigation Directorate (CID) at Wilford Hall Medical Center [59th Medical Wing, US AETC, Lackland AFB, San Antonio, Tx.]. At CID the quantitative determinations of Drugs of Abuse (DA) is part of a major, ongoing Program [related to methodologies of drug testing for the Armed Forces] under the Direction of Lt. Col. John Cody, Ph.D. In this report is discussed only one small aspect of this program namely an investigation of the usefulness of periodate oxidation as a means of removal of interfering, non-controlled OTC species in the testing for amphetamine and methamphetamine.

Amphetamine (AMP) and methamphetamine (MAP) are common drugs of abuse (DA) and testing for these compounds is of considerable interest to the Armed Forces. As mentioned below, immunoassay screening for these compounds is carried out on a large scale but the legal standing of the results of such screening may be compromised by interference due to the presence of some freely available OTC preparations, namely three phenylpropanolamines. It is of importance to remove these interfering agents before the results of immunoassay tests may be relied upon and similarly before reliable GC-MS data can be obtained. The removal of these interfering substances is made possible by oxidation using periodate.

Amphetamine and methamphetamine are CNS stimulants. Their stimulatory effect results from enhanced release of neurotransmitter catecholamines [norepinephrine and dopamine] from presynaptic terminals and by inhibition of neuronal reuptake. Amphetamine and methamphetamine have legitimate uses for treating narcolepsy, obesity and attention-deficit hyperactivity disorders. The drugs produce an initial euphoria with a feeling of well

being, improved self-esteem and apparent increased mental and physical capacity and for these reasons substance abuse of these drugs occurs frequently.

An important method for the determination of amphetamines (amphetamine and methamphetamine) is enzyme immunoassay. In such, drug-labelled glucose-6-phosphate dehydrogenase (G6PDH) competes with the free drug in the sample for the fixed amount of antibody binding sites. The unbound drug-labelled G6PDH enzyme activity is determined from the ability to convert β -nicotinamide adenine dinucleotide (NAD) to its reduced form, NADH. However, when a positive result is obtained a confirmatory test is usually required, typically by GC-MS analysis.

A number of readily available phenylpropanolamines have legitimate uses and are readily available as OTC drugs. These are: ephedrine (EP), pseudoephedrine (PEP) and phenylpropanolamine (PPA); the primary use of these drugs is as a bronchodilator and in "cold medicines" for the control of "runny nose" symptoms. Unfortunately, these phenylpropanolamines interfere with the quantitative determination of the more strictly controlled amphetamine and methamphetamine. This is particularly unfortunate as such agents as EP and PEP are not only readily available OTC but are often used in massive doses, far above recommended therapeutic levels; such high concentrations make the quantitative determination of AMP and MAP notably more difficult.

In large part, the present study was aimed at understanding and expanding on the study of the periodate oxidation of ephedrine (EP), pseudoephedrine (PEP) and phenylpropanolamine (PPA) by Buddha D. Paul and associates (at the Naval Drug Screening Laboratories) carried out in connection with their ongoing studies of reliable procedures for quantitation of amphetamines in urine.

The periodate ion (IO_4^-) is a moderately strong oxidizer due to the +7 oxidation state of the iodine. Presumably the iodine may be reduced [possibly stepwise] to oxidation states +6, and lower, in particular of course to -1, - i.e. the iodide ion. As would be expected, the rate of oxidation in aqueous solution must be strongly pH dependent. That the oxidative power of the IO_4^- ion is not greater than observed may be due in part to "steric hindrance": the oxygen atoms preventing more intimate, direct contact with the reducing molecule and thus limiting the rate of electron transfer.

While other methods are available for the determination of amphetamine (AP) and methamphetamine (MAP) we have, following the study by Paul et al., used a gas chromatographic-mass spectroscopic method (GC-MS).

MATERIALS EQUIPMENT AND PROCEDURES.

The main objective of this investigation was to determine the usefulness of periodate oxidation in removing EP, PEP and PPA from urine samples used in the GC-MS determination of AMP and MAMP. However, in the present study only a few sets of data were obtained using actual urine samples; for the majority of the work reported here only non-biological [aqueous] solutions were used. On the other hand, various extraction methods were employed to simulate the processing necessary in actual clinical work on urine samples. Once samples had been extracted and isolated, the solvents would be evaporated under controlled conditions, usually from slightly acidic solution so as to minimize possible losses of the relatively volatile amines. After evaporation to dryness (or very near dryness) suitably labelled internal standards for the MS determination of abundancies would be added.

A number of internal standards were used. These were commercial, deuterated samples, manufactured by either the Radian Company; the Alltech Company or by the Cambridge Isotope Laboratory.

Both methylene chloride [CH_2Cl_2] and 1-chlorobutane [$\text{CH}_3\text{CH}_2\text{CH}_2\text{CH}_2\text{Cl}$] were used for the extraction of the amines from aqueous solutions after the adjustment of pH to ensure the proper state of ionization of the amine in question.; however, whenever possible, the use of the 1-chlorobutane was preferred, both because of the lower toxicity of this material and also because of increased ease of separating the aqueous phase from the immiscible organic phase [by aspiration].

After evaporating the excess solvents, the compounds in the extracts were derivatized by adding 200 μl ethyl acetate to bring the amines into solution followed by reaction with 25 μl heptafluorobutyric acid anhydride (HFBA) [unless otherwise noted, at 60 °C]. After evaporating the excess derivatizing agent the final preparation was taken into solution using ethyl acetate (usually 100 μl) and 50 μl of this transferred into GC-MS sample vials (with conical inserts) and crimp-sealed.

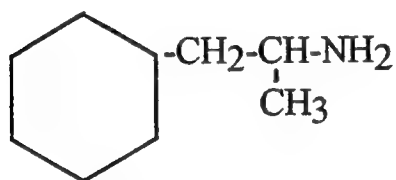
For the periodate oxidation experiments a saturated solution of the NaIO_4 was prepared (at room temperature). This corresponds to a 0.86 molal solution [density: 1.12 g/ml]. A number of stock solutions of the amines were prepared, usually in the range from 2 g/100 ml to 10 mg/100 ml and diluted as needed.

The GC-MS instrument used was a Hewlet Packard Gas Chromatograph and an HP Model 5890 Mass Spectrometer with an HP 5970 mass selective, quadrupole detector. Regrettably, several breakdowns occurred with this equipment during the authors tenure at CID, severely curtailing the use of the instrument as well as calling into question some of the results obtained. It appears that the main difficulty was not with the Gas Chromatograph but with the Mass Spectrometer.

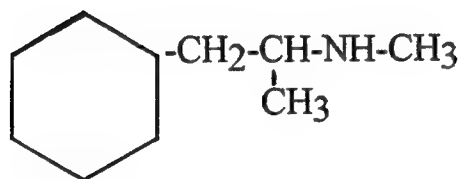
Contrary to the method used by Paul et al., no attempts were made to reduced the excess periodate with sodium thiosulfate or ascorbic after reaction. It is felt that in general this omission is not likely to affect the outcome of the experiments. However, as the NaIO_4 is relatively insoluble (see above), some spurious precipitation of the salt did occur in some samples. This precipitation was neglected as it is assumed that the amount of anlyte which could be removed by adsorption to the salt would be minimal.

In the Figure below are shown the chemical formulae for the main substances of interest in this study. Although the structures of ephedrine (EP) and phenylpropanolamine (PPA) differ by the additional -OH group at the 1-carbon from the structures of amphetamine (AMP*) and methamphetamine (MAP) it is hardly surprising that enough similarity in structure exists to confound the analysis of AMP and MAP. Hence the objective of the present study was to investigate the possibility of removing the EP and PPA from the samples being analyzed for AMP and MAP via a selective oxidation (with periodate).

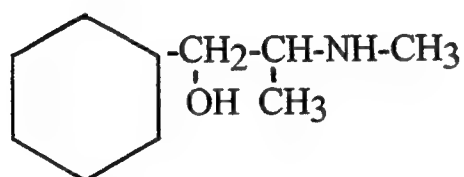
*. This notation, AMP, is somewhat unfortunate because of the frequent use of this abbreviation for adenosine-5'-phosphate. However, it should be easy from context to determine to which substance reference is made.



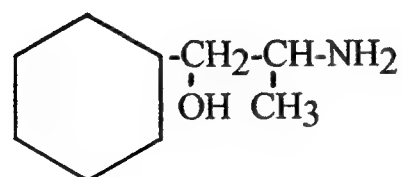
AMPHETAMINE (AP)



METHAMPHETAMINE (MAP)



EPHEDRINE (EP)



PHENYLPROPANOLAMINE (PPA)

FIG. 1

EXPERIMENTAL

To illustrate the experimental technique, a typical experiment is described below (Run # IB10). Date: July 22 - 25, 1995.

The objective: a comparison of the quantitation of (+)- ψ -ephedrine and (-)- ψ -ephedrine.

Materials: both samples of ephedrine were from Sigma Co., respectively Lots 96F05311 and 104F0738.

Calibration data [Run IB10Y] were obtained using new stock solutions of (+)- ψ -EP; (-)- ψ -EP and (+)-EP. The stock solutions were made to contain 25.0 mg/250 ml water = 0.10 mg/ml stock solution. The solutions tested were made by adding the amounts indicated in the Table below.

(All volumes in μ l, except for the water: in ml)						CONC. (ng/ml)				
Sample #	(+)- ψ -EP	(-)- ψ -EP	(+)-EP	PPA	Int'l standard	water	(+)- ψ -EP	(-)- ψ -EP	(+)-EP	PPA
20	100	0	0	0	100	1.80	5000	0	0	0
21	0	100	0	0	100	1.80	0	5000	0	0
22	0	0	100	0	100	1.80	0	0	0	0
23	0	0	0	100	100	1.80	0	0	0	5000
24	100	100	100	100	100	1.50	5000	5000	5000	5000
25	100	100	100	100	100	1.50	5000	5000	5000	5000
26	20	20	20	20	100	1.82	1000	1000	1000	1000
27	20	20	20	20	100	1.82	1000	1000	1000	1000
28	50	0	0	0	100	1.85	2500	0	0	0
29	0	50	0	0	100	1.85	0	2500	0	0
30	0	0	50	0	100	1.85	0	0	2500	0
31	0	0	0	0	100	1.90	0	0	0	0

Concentration of Internal Standard: 500 ng/ml AMP-d6 and MAP-d8

Added: 100 μ l 1.0 Molar NaOH

Extraction with n-C₄H₉Cl. To the extract in the organic phase was added 100 μ l 1% HCl in CH₃OH

In the table below, the concentrations are listed in ng/ml. Columns A - E list the known amounts present while Columns F, G and I lists the amounts found (observed). The quantities in Columns I and J are defined below.

ABBREVIATIONS of Column Headings.

A	(+) PEP
B	(-) PEP
C	EP
D	PPA
E	$\Sigma \text{ PEP} - \text{i.e. } \Sigma [(+) \text{ PEP} + (-) \text{ PEP}]$

F	$[\Sigma \text{ PEP}]_{\text{obs}}$
G	$[\text{EP}]_{\text{obs}}$
H	$[\text{PPA}]_{\text{obs}}$

Derived Quantities

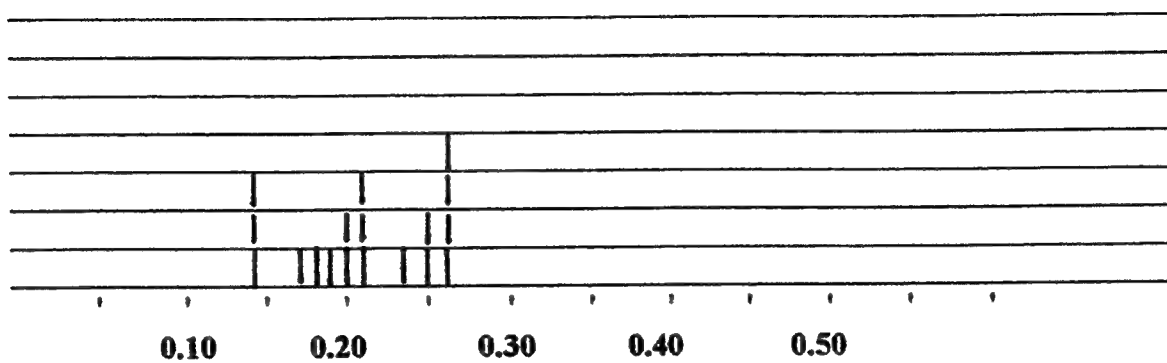
I	$[\text{EP}]/[\Sigma \text{ PEP}]_{\text{obs}}$
J	$[\text{EP}]/[\Sigma \text{ PEP}]_{\text{prep.}}$

FILE: AFREP95E

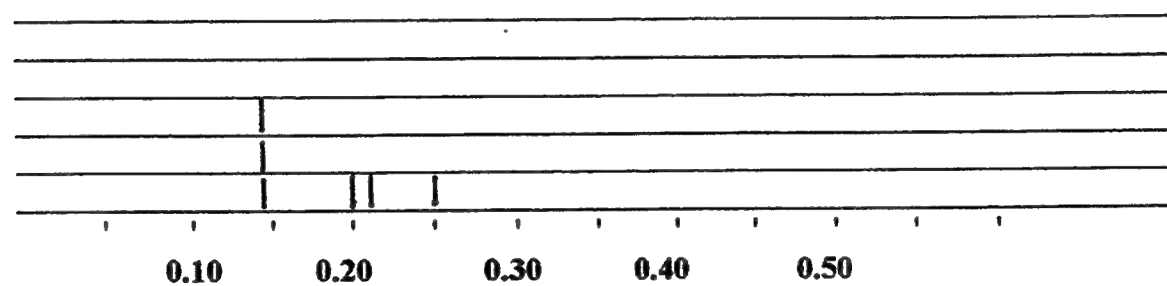
#	A	B	C	D	E	F	G	H	I	J
1	5000				5000	634	708	24	1.17	0.14
2	5000				5000	1573	1257		0.80	0.25
3	2500				2500	803	517		0.64	0.21
4	2500				2500	749	500		0.67	0.20
5	1250				1250	291	180		0.62	0.14
6	1250				1250	298	172		0.58	0.14
7		5000			5000	1344	1281		0.95	0.26
8		5000			5000	1458	1153		0.79	0.23
9		2500			2500	587	471		0.80	0.19
10		2500			2500	664	461		0.69	0.18
11		1250			1250	275	210		0.76	0.17
12		1250			1250	295	244		0.83	0.20
13		1250			1250	263	330		1.25	0.26
14	2500	2500			5000	1361	1283		0.97	0.26
15	2500	2500			5000	929	1026	0.5	1.10	0.21
16	2500	2500			5000	1310	1256		0.96	0.25
17				2500		0	5[?]			
18	2500	2500		2500	5000	1451	1044	2930	0.72	0.21
19	2500	2500		2500	5000	1330	1308	2760	0.98	0.26

Some of the results from this Table are shown graphically, below.

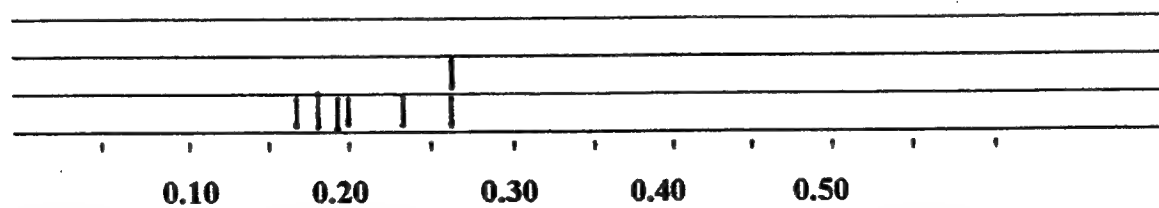
I) $R_2 = [EP]_{\text{obs}}/[PEP]_{\text{prep}}$



II) $R_2' = [(+)\text{-}\psi\text{-EP}]/[PEP]_{\text{prep}}$

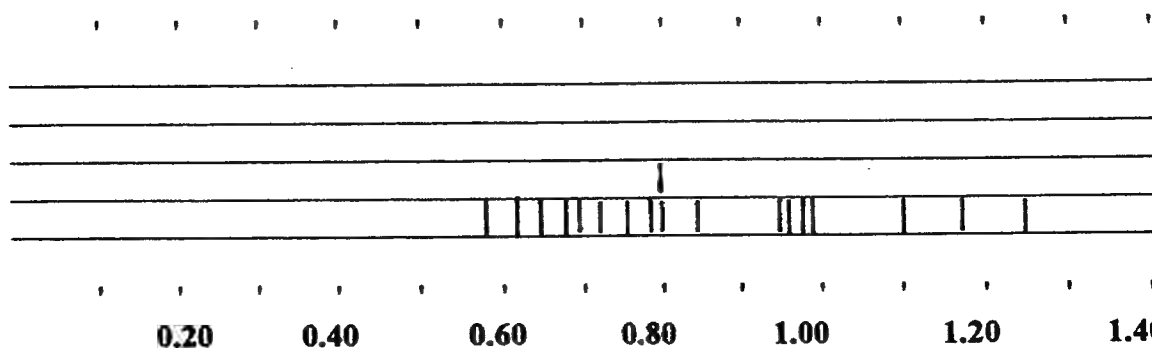


III) $R_2'' = [(-)\text{-}\psi\text{-EP}]/[PEP]_{\text{prep}}$



Graph of $R_1 = [EP]/[PEP]_{\text{obs}}$

FIG. 2B



Observed concentration of PEP versus amounts present.

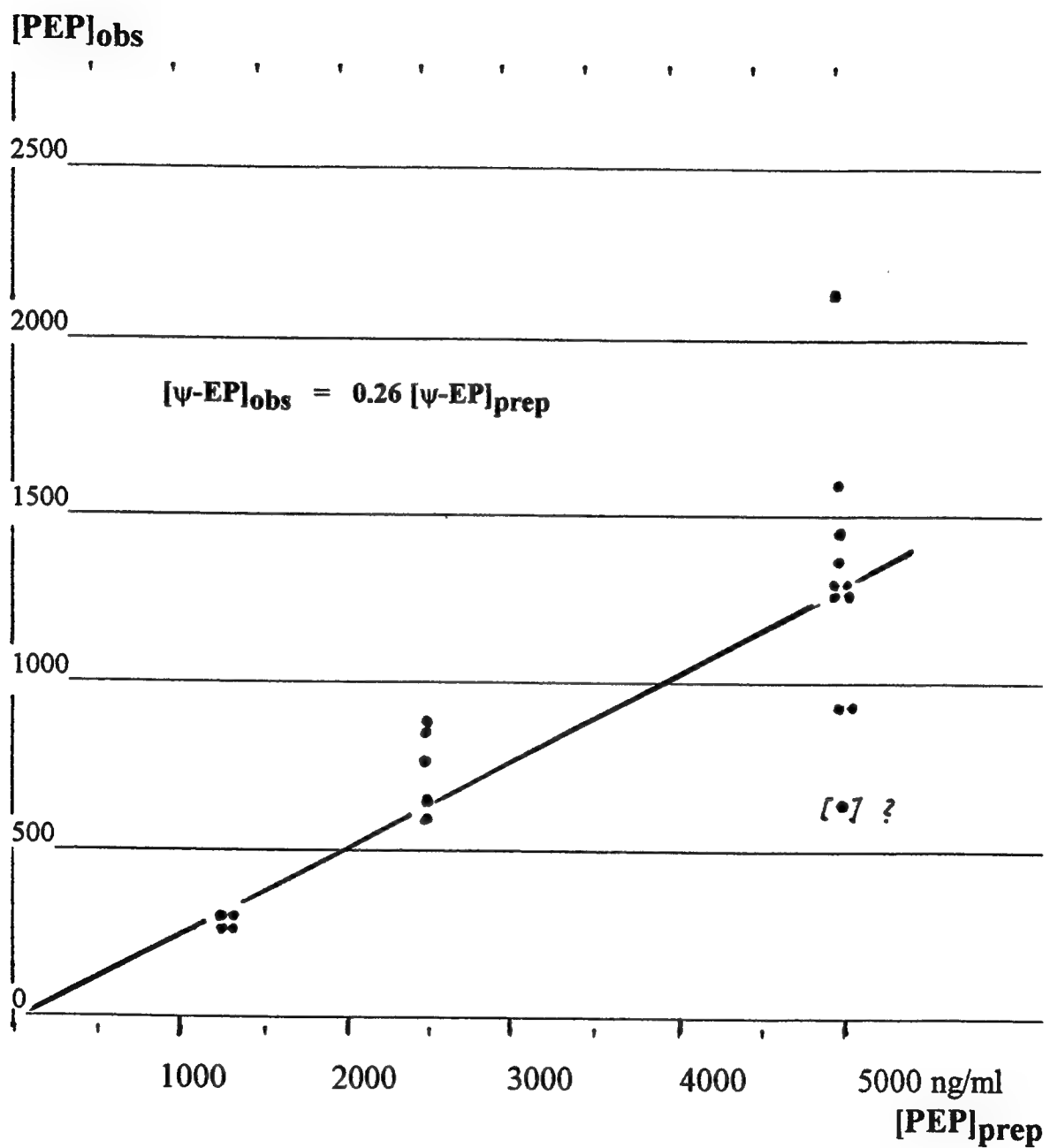


FIG. 3

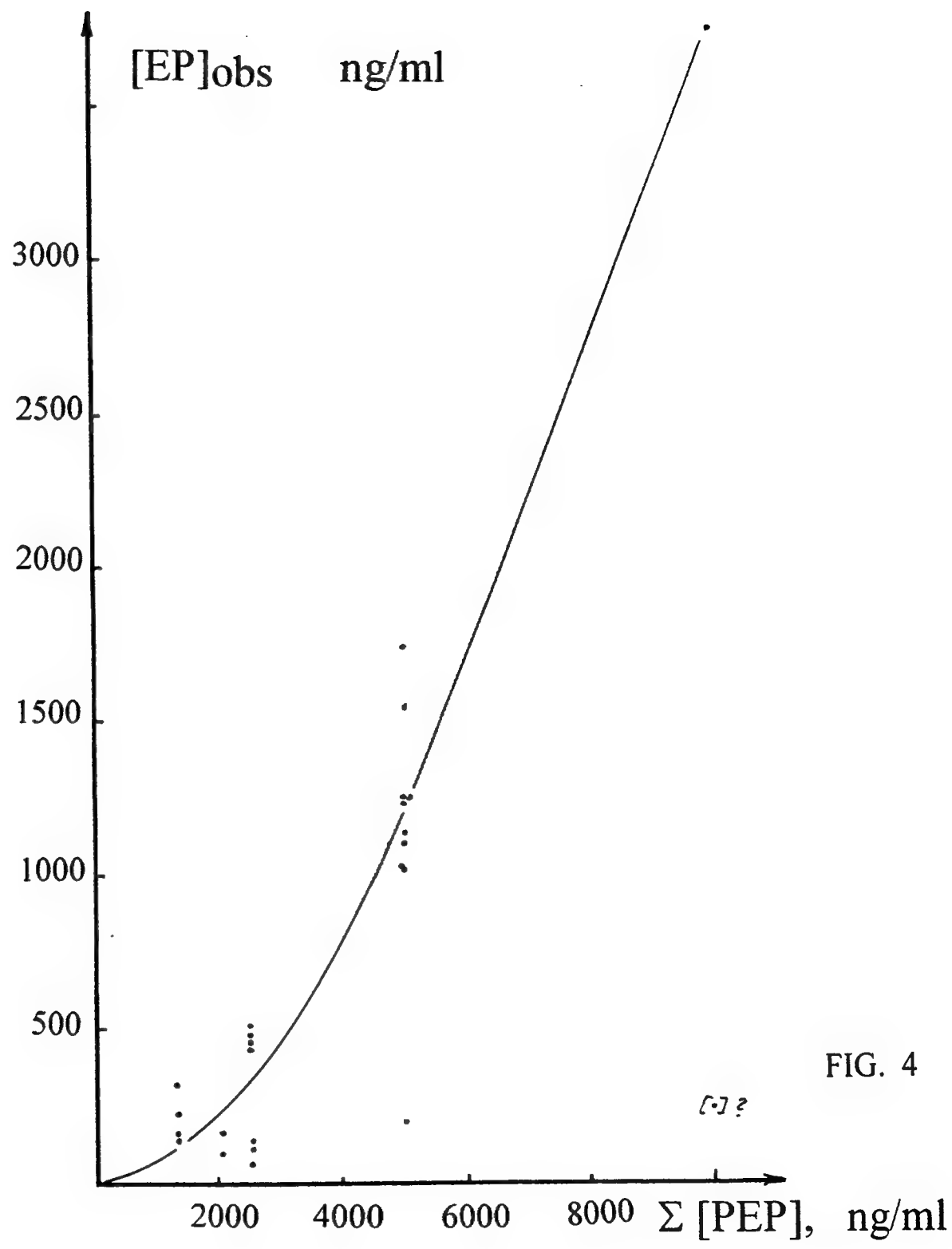


FIG. 4

[?]

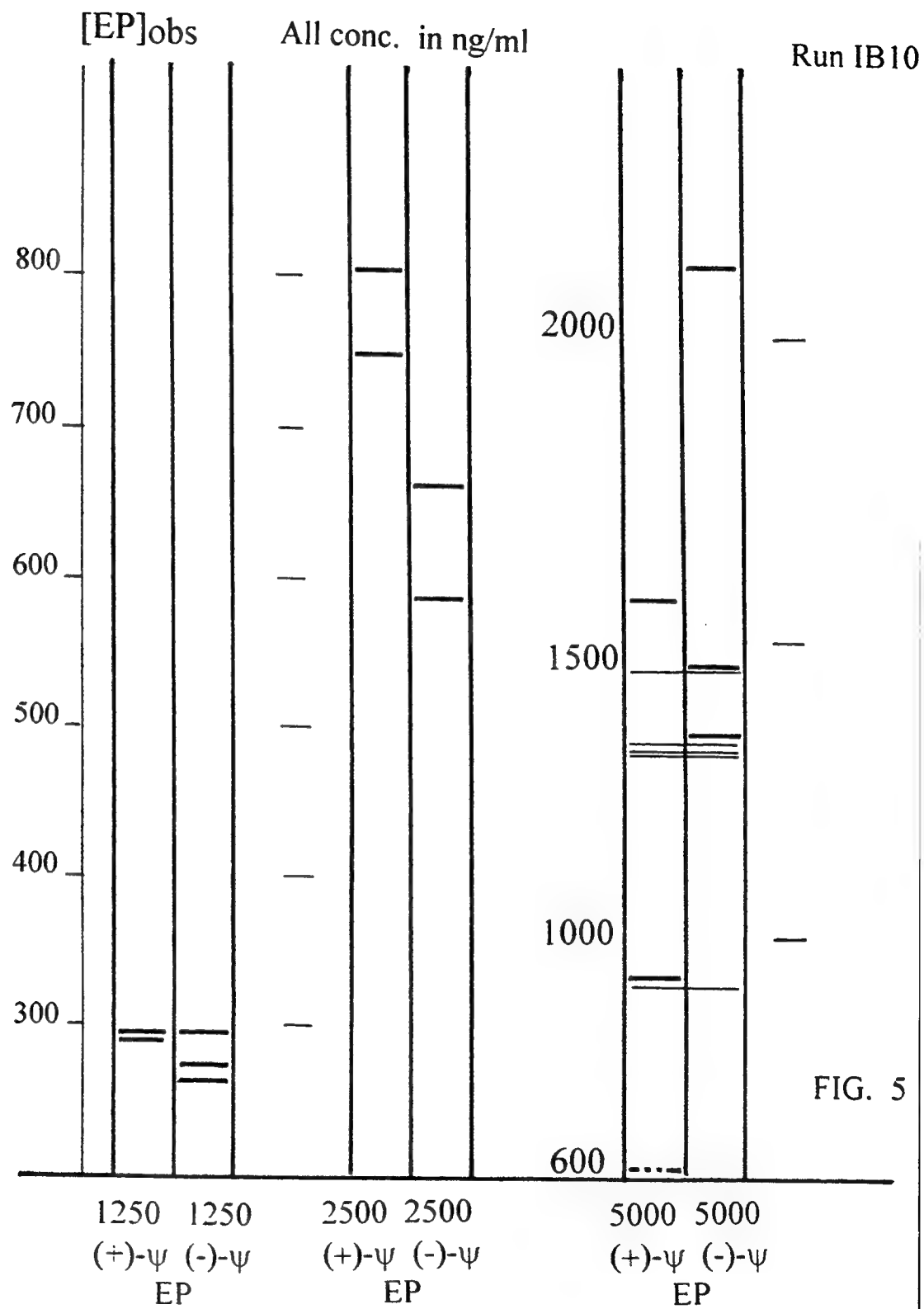


FIG. 5

Thin lines: Data from mixtures of (+)-ψ and (-)-ψ

The data shown in Fig. 2 demonstrate that while the expected ratio of 1.00 for the ratio of the observed concentration of ephedrine to the actual, known concentrations was never attained there was some degree of consistency in the results. Thus, an essentially constant "correction factor" of 5.0 will bring all the ratios to near 1.00, within $\pm 30\%$. To be sure: the result is not spectacular but possibly useful - at least likely of use in a screening program.

Also shown in Fig. 2 are the ratios (implied in the top graph) for the two different isomers of ephedrine (respectively the (+)- ψ EP and (-)- ψ EP). It is seen that there is no statistically significant difference between the two different samples.

Finally, the lower portion of Fig. 2 shows the ratio of [EP] to the *observed total concentration* of PEP. On the average this ratio should be 1.00 and again this is observed albeit with a scatter of about $\pm 40\%$.

The data from the Table above are also presented in Fig. 3. Again, while the slope of the curve ideally should be 1.00, at least the data show, as discussed above, that the method is approximately reliable and may be used with a proper "correction factor".

Another set of data from the Table of results from Run IB10 are shown in Fig. 4.

Finally, in Fig. 5 is shown the observed amounts of EP (in ng/ml) for various initial concentrations of EP in the samples. It is again apparent that there are no statistically significant differences between the results using (+)- ψ EP and (-)- ψ EP

EXPERIMENT RUN IB02 (JUNE 21-26, 1995)

This experiment was designed to test the reproducibility of direct concentration determinations of the three propanol amines: EP, PEP and PPA.

#	SAMPLES PREPARED			OBSERVED		
	[PEP]	[EP]	[PAP]	[PEP]	[EP]	[PPA]
1a	50			50		
1b	50			36		
2a	500			552	49	3
2b	500			568	0	2
3a	5000			31857	886	109
3b	5000			74964	79309	167
4a		50		1576		
4b		50		820		
5a		500		1538	2087	4
5b		500		466	1437	
6a		5000		-	-	-
6b		5000		40540	$1.79 \cdot 10^5$	338
7a			50	77		73
7b			50	200		110
8a			500	2397		1257
8b			500	3280		2245
9a			5000	2026		75005
9b			5000	5332		$5.9 \cdot 10^5$
#	[PEP]	[EP]	[PAP]	[PEP]	[EP]	[PPA]
1d	10000	10000	10000	$2.39 \cdot 10^6$	$8.9 \cdot 10^6$	$1.8 \cdot 10^5$
1e	10000	10000	10000	$2.6 \cdot 10^6$	$9.3 \cdot 10^6$	$3.2 \cdot 10^5$
1f	10000	10000	10000	$3.8 \cdot 10^6$	$3.5 \cdot 10^5$	$2.0 \cdot 10^5$
2d	5000	5000	5000	$7.4 \cdot 10^6$	$3.0 \cdot 10^5$	$1.4 \cdot 10^5$
2e	5000	5000	5000	$2.1 \cdot 10^6$	$2.6 \cdot 10^5$	$0.5 \cdot 10^5$
2f	5000	5000	5000	$9.7 \cdot 10^6$	$7.0 \cdot 10^5$	$2.8 \cdot 10^5$
3d	<u>1000</u>	<u>1000</u>	<u>1000*</u>	$8.1 \cdot 10^4$	$2.9 \cdot 10^4$	3126
3e	1000	1000	1000	$7.3 \cdot 10^4$	$1.3 \cdot 10^5$	6014
3f	1000	1000	1000	$5.6 \cdot 10^4$	$9.5 \cdot 10^5$	2763

#	[PEP]	[EP]	[PAP]	[PEP]	[EP]	[PPA]
4d	100	100	100	2679	7827	164
4e	100	100	100	3234	4788	191
4f	100	100	100	3084	2596	175
5d	10	10	10	707	5637	48
5e	10	10	10	0	0	0#
5f	10	10	10	0	0	0#
6d	0	0	0	173	0	0

*: Used as Standard for all the runs.

ISTD 2 not found!

The results from Run IB02 shown in the table above are puzzling at best and overall rather troublesome and distressing.

For samples 1a, 1b, 2a, 2b the agreement between known and observed values was fair, but far from satisfactory. However, for most of the other samples the observed amounts *far* exceeded the known amounts for unknown reasons. The results for samples 1d through 3f are particularly puzzling as the observed amounts exceeded the known amounts by factors of about 100 or more. At this time we have no explanation to offer for these enormous discrepancies.

In a separate experiments (IA01,a,b,c data not shown) it was found that in the periodate oxidation in strongly alkaline solution (pH about 12) a constant fraction of MAP was converted to AMP, apparently independently of the time of reaction and independent of temperature during the oxidation [room temperature versus 60 °C]. This result is in complete disagreement with the findings of Paul et. al. and this difference does not appear to be related to Inlet Port temperature or Interface-Detector temperature. We are at a loss to explain this difference but it may be important to note that the data reported by Paul et al. were obtained in essentially pure water (actually, urine) while the experiments reported here were carried out in about 33 vol-% CH₃OH. One may speculate that the periodate was reduced by reaction with the methanol and thus affected the intended oxidation. Unfortunately, subsequent experiments to investigate the role of the methanol (IA02, IA03) were not successful because of a number of problems, mostly instrumental.

A number of experimental difficulties hampered this investigation during the summer. The problems were mostly instrumental, particularly with the functioning of the mass spectrometer itself, but additional problems were encountered with the associated computer hardware and software. Also some problems were encountered with the dedicated Printer for the GC-MS instrument. On a number of occasions outside help was needed (primarily from the Hewlett-Packard Service Group) but delays of several days occurred frequently. Because of these difficulties far less progress was achieved than originally anticipated; however, most (or all) of the instrumental problems may have been resolved by now. It is also worth noting that the analysis of ephedrine is generally considered difficult although there are no a-priori reasons why this should be more difficult to analyze for than other, related compounds.

SUMMARY

Because of the numerous experimental difficulties which were encountered in this study it is not yet possible to judge the utility of the proposed oxidation by periodate of phenylpropanolamines in the determination of amphetamine and methamphetamine. On the other hand, a great deal was learned from this study re. the mechanics and procedures of the GC-MS determination of these drugs of abuse. The determination of ephedrine by the GC-MS methods is apparently intrinsically difficult [and the experimental breakdowns of the analytical equipment certainly added to the problems in the quantitation of EP]. A variety of (minor) possible modifications to the procedure should be considered, including varying the ratio of derivatizing agent to sample; performing the derivatization at higher temperatures and/ allow more time for the reaction to be completed; insuring more complete removal of water from the sample before derivatizing; and possibly consider a different derivatizing agent altogether (although this would require a great deal of additional effort to delineate the optimal mass fragments to be measured in the MS). It is difficult to find faults or major weaknesses in the paper by Buddha Paul et al., and it must therefore be concluded that the procedure as outlined by these authors is indeed a valid one. It is my hope that I may be allowed to continue to work on this project next summer.

REFERENCES.

Paul, Buddha D., Marily R. Past, Ronald M. McKinley and Jacqueline D. Foreman. "Amphetamine as an artifact of methamphetamine during periodate degradation of interfering ephedrine, pseudoephedrine, and phenylpropanolamine: An improved procedure for accurate quantitation of amphetamines in urine". J. Analytical Toxicology, Vol. 18, 331 - 336, 1994. [- and references therein].

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